POLITECHNIKA LUBELSKA

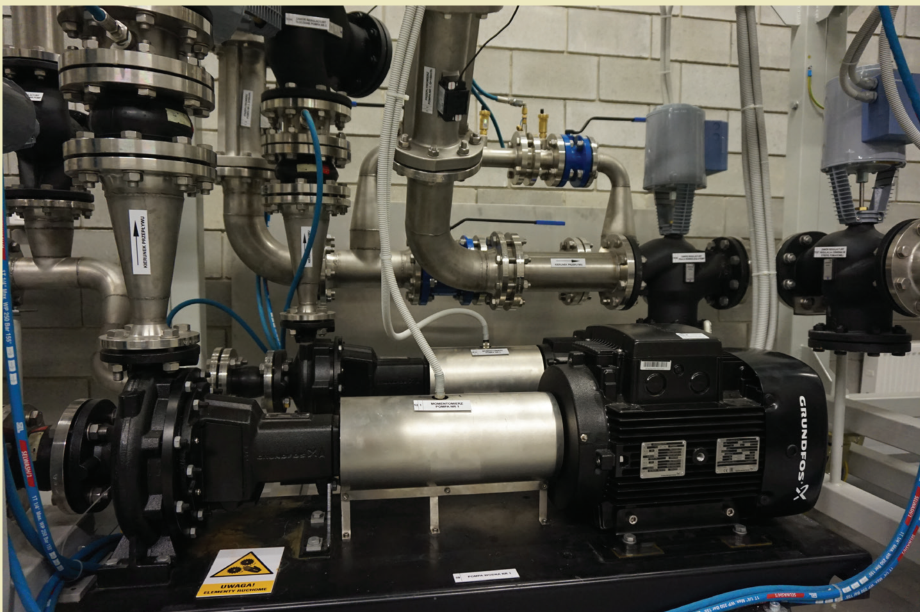
MONOGRAFIE

Water Supply and Wastewater Removal

edited by

Henryk Sobczuk

Beata Kowalska



Lublin 2016

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Monografie – Politechnika Lubelska

Politechnika Lubelska
Wydział Inżynierii Środowiska
ul. Nadbystrzycka 40B
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Lublin University of Technology
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Publication approved by the Rector of Lublin University of Technology

ISBN: 978-83-7947-200-0

Publisher: Lublin University of Technology
ul. Nadbystrzycka 38D, 20-618 Lublin, Poland
Realization: Lublin University of Technology Library
ul. Nadbystrzycka 36A, 20-618 Lublin, Poland
tel. (81) 538-46-59, email: wydawca@pollub.pl
www.biblioteka.pollub.pl
Printed by : TOP Agencja Reklamowa Agnieszka Łuczak
www.agencjatop.pl

The digital version is available at the Digital Library of Lublin University of Technology: www.bc.pollub.pl
Circulation: 100 copies

Contents

Water supply and water discharge: challenges and concept of responces – context of climate change and exhaustions of water resources

S. Boychenko[1], R. Havryliuk[2], Ya. Movchan[3, 4], O. Tarasova[4], V. Sharavara[4], S. Savchenko[4]

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Abstract

For a long time the natural water resources of Ukraine experienced a heavy anthropogenic pressure resulting in the negative environmental changes. The examples of such changes related to forecast of impact of possible tendencies of climate change are considered in this article.

In 2015 year the general hydrological situation in the basins of the Ukrainian rivers and reservoirs was rather dangerous due to the smallest volume of water in the reservoirs over all the period of their exploitation. Such situation occured due to the complicated climate conditions (climate aridization), and consequent increased water consumption.

The intensive water pollution by wastewater from industrial enterprises and municipal companies, wastewater from animal farms, surface run of snow melting as well as by rain waters contaminated by the different pollutants from the agricultural and urban areas, and exploitation of water transport make the situation in Ukraine even more complicated (*DEFRA, 2010 Europe; European; Feyen, 2009*).

For the analyses of the long-term regional changes of climatic fields in Ukraine the empirical data of observations obtained from the network of meteorological stations were used. The semi-empirical models of transformation of annual and seasonal courses of climatic conditions (surface temperature change and precipitation) in Ukraine under the influence of global warming were developed. For comparison the climatic field of the annual and seasonal temperatures and the annual sum of precipitations for the Holocene Optimum were also used. The expected features of climate change and consequences for Ukraine were forecasted. The coastal regions of the Black Sea and the Sea of Azov, the Carpathians, mountains of Crimea and steppe were recognized as the territory of Ukraine the most vulnerable to climate changes.

The answer to this challenge should be a change in attitude to water: maximum economy, adequate pricing, termination of pollution, groundwater use, maximum

treatment and swivel water use, recovery of natural rivers, lakes, flood plains, deltas, coastal zones, swamps and wetlands, reduction of the surface area of reservoirs. As new legal instrument the updated Water Code of Ukraine lined up to the European Union water legislation and the Protocol on Strategic Environmental Assessment should be applied widely.

Keywords

Climate change, water resources, water supply, wastewater discharge, forecast and trends of the state of water resources, measures towards water policy in municipal sector

1 Introduction

The natural water resources of Ukraine for many years experienced a heavy anthropogenic pressure, resulting in the negative environmental changes and the consequent economic losses. Examples of such changes related to the possible scenarios of climate change impacts are presented in this article.

To some extent the climatic conditions may result in decrease in the water volume in the water bodies due to increased evaporation caused by of the elevated surface temperature and reduced precipitation (*Feyen, 2009*).

In 2015 year the general hydrological situation in the basins of many rivers and reservoirs of Ukraine was characterized as dangerous due the lowest volume of water during the total time duration period of their exploitation. Such situation occurred due to a very hot and dry weather conditions (climate aridization), and the consequent increase in the water consumption.

These factors resulted in the reduced water discharges from reservoirs to the minimal allowable sanitary and environmental values and significant drawdown of the Dnipro reservoir cascade (6 reservoirs) and the Dnister reservoir. Free volume of the Dnipro reservoir cascade in September of this year was equal to 5.1 km^3 where during the last few years it did not exceed 2/75±0./25 km^3.The water discharge of the Dnister reservoir decreased to 105–110 m^3/sec when the minimal environmentally allowable was equal to 100 m^3/sec (Fig. 1). Water volume of the Southern Bug river in August and September 2015 was approx. 12–15% lower than the monthly average.

The intensive water pollution by the various sewage from industrial enterprises and municipal companies, wastewater from animal farms, run of snow melting and polluted storm water from the agricultural and urban areas as well as exploitation of water transport complicate the situation.

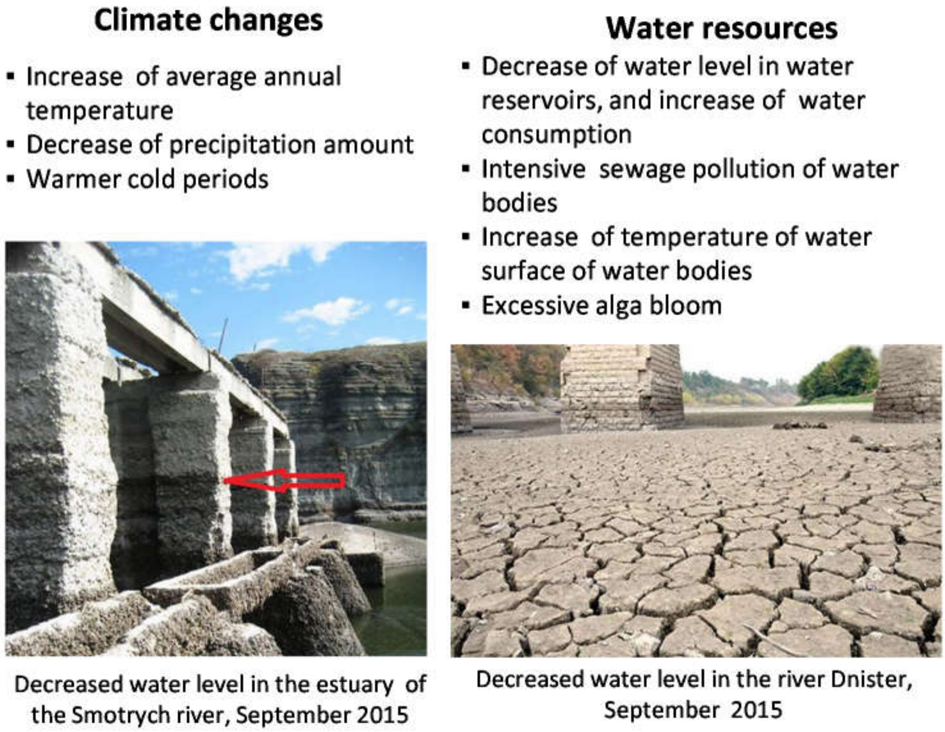

Fig. 1. Consequences of climate changes, and its influences on water resources

2 Materials and Methods

For the analyses of long-term regional changes of climatic fields in Ukraine the empirical data of observations obtained from the network of meteorological stations were used. The applied meteorological stations were chosen to meet the following requirements (*Boychenko, 2007; Voloshchuk, 2002; Voloshchuk, 2003*):

- observations by meteorological stations were started not later than 1900;
- missing observations by meteorological stations do not exceed 30% for the period 1900–2000.

Only 25 of such stations operate at the territory of Ukraine. It is supposed that the main reason of the regional changes of climatic conditions in the territory of Ukraine for last 100 years is the global warming because of anthropogenic global atmosphere pollution by "green-house" gases. The analyses of dependence of meteorological parameters on time (seasonal fluctuations) and on the altitude above sea level, and also their geographical distribution at the territory of Ukraine was performed in this paper. Such complex research represents the special interest of Ukraine related to its sharply expressed orography (for example, Ukrainian

Carpathians, Crimean Mountains, Volynsk and Donetsk elevations) and also with the features of distribution of anomalies of atmospheric precipitation at its territory.

The climatic field of annual and seasonal temperatures and the annual sum of precipitations for the Holocene Optimum (ΔT ~ 1 ºC) were also used in our studies (*Oliver and Fairbridge, 1987; Velichko, 2002*).

3 Results and Discussion

3.1 Water supply and wastewater discharge in Ukraine: practice and state of art

The municipal and industrial water demands in Ukraine are satisfied presumable by surface water, the total share of which in water supply constitutes approx. 80% (*Міністерство, 2013*). Surface water is more affordable in comparison to groundwater but – much more vulnerable to the technogenic pollution. Even in the areas of unfavorable natural conditions for use of surface water due to extremely scarce water resources and their high mineralization (East and South of Ukraine) water pipes for water supply were constructed from the large rivers, mostly – from the Dnipro river.

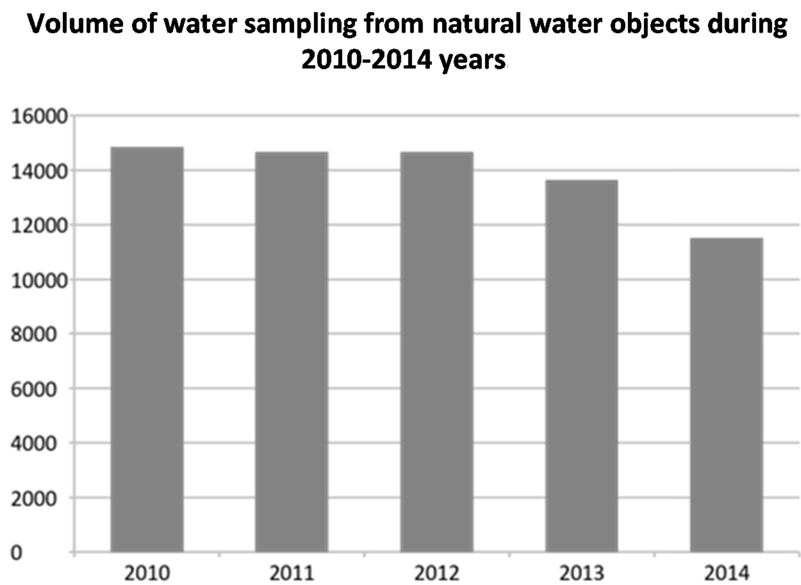

Fig. 2. Volume of water intake from natural water objects during 2010–2014 years

The intensive use of surface water for the purposes of consumption and energy generation is accompanied by the regulation of river flow (volume of water intake from natural water objects during 2010–2014 years was presented in Fig. 2).

As a result, the water reservoirs and pounds accumulated approximately 58 billion m^3 of water. This volume exceeds the annual flow from all rivers of the country. Regulation of most of rivers reached or even exceeds the upper economic and environmentally sound water-allowable limit up to the point of environmental destruction (above 75% of total length of channels at optimum 25–30%) – dramatically reduced and often totally destroyed the self-purification capacity of rivers (*DEFRA, 2010; Державна, 2014, 2015; Feyen, 2009; Національний*). Indicators of the general water drainage during 2010–2014 years were showed in Fig. 3 (*Державна, 2014, 2015*).

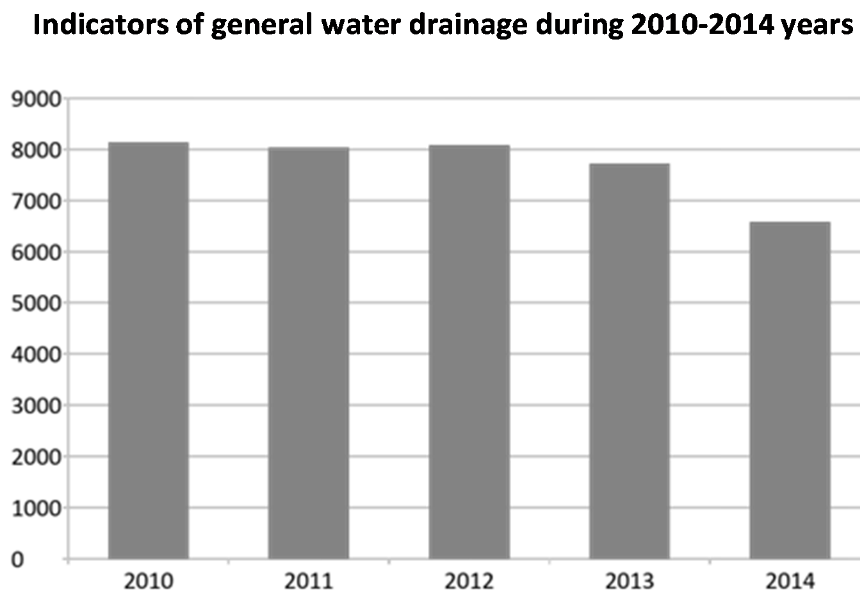

Fig. 3. Indicators of general water drainage during 2010–2014years

State of both types, the small and large rivers of Ukraine steadily continues to deteriorate.

The chemical and radiological indicators (information of state monitoring system in 2013) show that the quality of surface water is unsatisfactory. In more than 90% of the control points the standard allowable concentrations of pollutants or indicators of physical and chemical state of surface water were exceeded. In most cases these indicators were: chemical oxygen demand and biochemical oxygen demand, total iron and color. Manganese, dry residue, hardness, sulfates;

petrochemicals also exceeded the maximum allowable concentrations (*DEFRA, 2010; Feyen, 2009; Міністерство, 2013*). In addition, the phosphates, presence of which is a result of influence of sewage waters at river systems, were detected in the tested surface water.

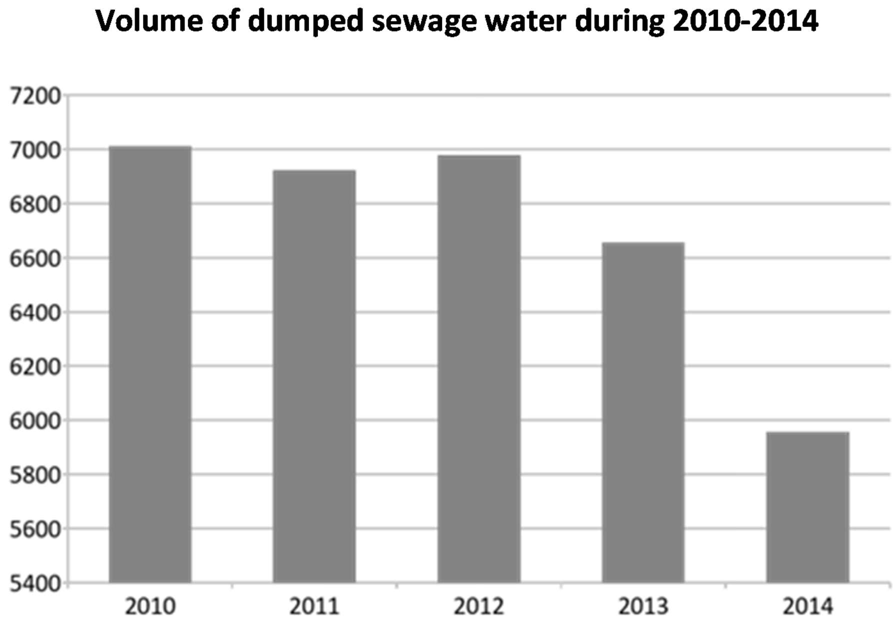

Fig. 4. Volume of dumped sewage water during 2010–2014 years

The official statistics says that 440 million m^3 of wastewaters were discharged into surface waters in 2013. Including the polluted water constituted 1717 million m^3 (23%), normatively treated – 1477 million m^3 (20%), normatively cleaned without treatment – 4246 million m^3 (57%) (*Міністерство, 2013*). The 881 enterprises discharge wastewaters into the surface water bodies. Sources of municipal and industrial wastewater discharge into water bodies or through a system of urban sewage. In 2013 (according to the official data) 45.2 thousand tons of suspended solids, 375.6 tons of petrochemicals, 1006 thousand tons of sulfates, 782.5 thousand tons of nitrites, 253.4 tons of synthetic detergents, 760.5 tons of iron, 7.8 thousand tons of phosphates, etc. were discharged with wastewaters into the surface water bodies (*Державна, 2014, 2015*). Volume of dumped sewage water during 2010–2014 was shown in Fig. 4 (*Державна, 2014, 2015*).

In addition, the quality of surface waters is also negatively affected by discharge of pit mine water discharged almost without any treatment into surface water bodies in the annual volume of 661 million m^3.

3.2 Climate change and consequences for Ukraine

The analysis of data of instrumental observations of a network of meteorological stations of Ukraine for last 100–130 years showed that its climatic conditions reacted to the global warming as follows (*Boychenko, 2008; Boychenko, 2015; Voloshchuk, 2003; Voloshchuk, 2010*):

- the annual temperature increased by 0.6±0.2 °C/100 years which approximately coincides with estimations of a level of the global warming (Fig. 5);
- the process of alignment of an annual temperature field was revealed: in northern and north-east regions the annual temperature increased by 1.0±0.2 °C/100 years; in southern and south-west regions of Ukraine – only by 0.5±0.1 °C/ 100 years;
- decrease in the amplitude of a seasonal course of temperature by ~0.4–0.5°C (effect of continentalization): significant warming in the cold period of year (1.0–2.0 °C/100 years), for spring (1.5–2.0 °C/100) years; warming was insignificant in summer months;
- insignificant increase in the annual sums of precipitations (5–7% for 100 years) (Fig. 6);
- general alignment of a climatic field of the annual sums of precipitations was revealed. In northern and north-west regions of Ukraine, where the annual sum of precipitations was relatively high (650–750 mm/year), it decreased approximately by 10–15%; in southern and south-east regions, where the annual sum of precipitations was relatively low (350–450 mm/year), it increased approximately by 10–15%;
- decrease in the sum of precipitation for some months: spring – May, summer-autumn – August–September;
- increase in the repeated anomaly of high temperatures in May for the period 1891–2011 (in XX century – 16/5–17/5 °C and in XXI – 18/0–18/8 °C).

Surface temperature and precipitation changes in Ukraine were used for elaboration of the regional scenarios:

1. Scenarios of the global surface temperature change for the end of the 21st century (*Climate, 2013*):

- it is likely that not to exceed 2°C for RCP4.5 – (Δ T ~ 2.0 °C);
- it is likely to exceed 2°C for RCP8.5 – (Δ T ~ 4.0 °C).

2. Semi-empirical models of transformation of the annual and seasonal courses of climatic conditions (surface temperature change and precipitation) in Ukraine under influence of the global warming (*Boychenko, 2007; Boychenko, 2008; Voloshchuk, 2003; Voloshchuk, 2004; Voloshchuk 2010*).

3. Climatic field of annual temperatures and the annual sum of precipitations for the Miculino ($125 \cdot 10^3$ years, ΔT ~ 2/0–2/5°C) and Pliocene Optimum ($2.3–3 \cdot 10^6$ years, ΔT ~ 3/0–4/5°C) (*Oliver and Fairbridge, 1987; Voloshchuk, 2002*).

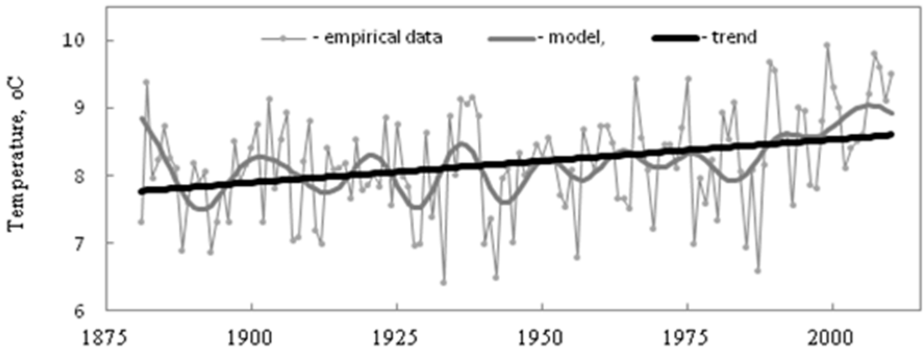

Fig.5. Century course of fluctuations of annual temperature in Ukraine for the period 1881–2010

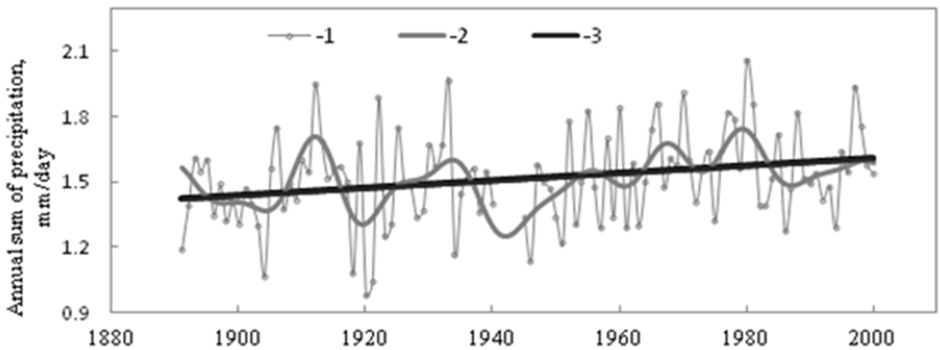

Fig.6. Century course of fluctuations of annual sum of precipitation in Ukraine for the period 1885–2005

Thus, the regional scenarios of surface temperature change in Ukraine for the 2050 (Fig.7) are the following (*Boychenko, 2008; Boychenko, 2015; Voloshchuk, 2003; Voloshchuk, 2010*):

- scenarios 1: it is likely than not to exceed (Δ T ~ 1.4±0.2 °C) ;
- scenarios 2: it is likely to exceed (Δ T ~ 2.4±0.3 °C).

The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be some regional exceptions (*Climate, 2013; Jones, 1999;Voloshchuk, 2004*). Therefore, regional scenarios of precipitation change in Ukraine for the 2050 the following is expected (*Boychenko, 2007; Boychenko, 2015; Voloshchuk, 2010*).

Scenarios 1: increase in the annual sums of precipitations on 10±5% and aridity of climate in the warm period of year (May and August).

Scenarios 2: differential spatial distribution of annual sums of precipitations, namely increase in the northern, northwest and northeast regions by 15±5% and decrease in the southern, southeast and southwest regions by 15± 5%.

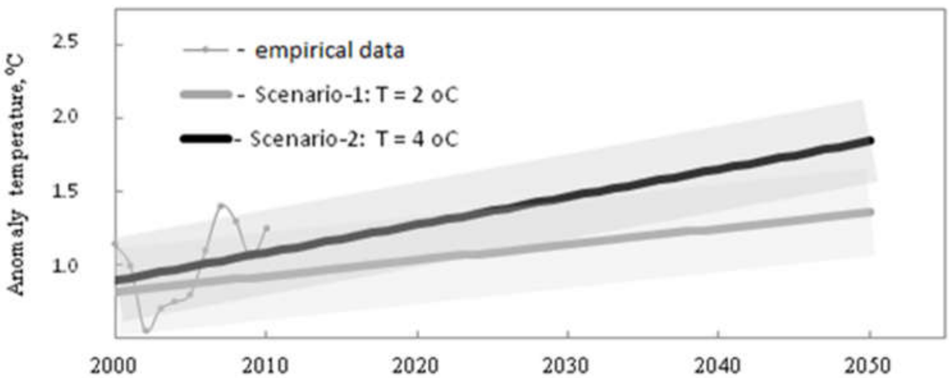

Fig. 7. Regional scenarios of surface temperature change in Ukraine for the 2050

The following features of climate change and consequences for Ukraine are expected (*Boychenko, 2008; Kobak, 1992; Tkachenko, 2014; Velichko, 2002*):

- effect of the approximate synchronization of fluctuations of levels of the Black Sea and the Sea of Azov with fluctuations of the World Ocean. Century course of a level of the Black Sea and the Sea of Azov for the period 1923–2007 increased by 12–15 cm/100 years and in the scenario for period 2050 a level of sea will increase till 25–30 cm – $\Delta T \sim 2\ ^oC$;
- activization of catastrophic shifts and deformations in mountain regions of the Carpathians mountains and the Crimea through changes of a regime of humidity, water balance, ground and subsoil waters;
- increase in the repeatability of catastrophic floods in region of the Ukrainian Carpathians mountains caused by an intensification of heavy rains and intensified by deforestration;
- intensification of meridional circulation of an atmosphere which will result in the increase in the repeatability of some anomaly synoptic formations above Ukraine;

- structural drift of steppe phytosystems in Ukraine under the influence of climate changes and in line with the scenarios for first half of the XXI century. The analysis of ratio of the basic ecobiomorphological components in phytocoenosis of the Ukrainian steppes at the second half of the XX century and in the beginning of the XXI century revealed the tendency of degradation of xero-morphic component by 30±10% and the reverse tendency of increase of mezo-morphic component by 10±5% and lignostic components by 20±10%.

So, the most vulnerable to climate changes in territory of Ukraine are the coastal regions of the Black Sea and the Sea of Azov, the Carpathians and mountains of the Crimea and steppe.

4 Summary and Conclusions

Systematic analysis of the current trends in climate change, environmental state of the river basins of Ukraine and peculiarities of management and protection of water resources showed that most urgent problems are as follows:

- increase in the temperature at water surface of water bodies;
- reduction in the water content of water bodies due to the increased evaporation upon increased surface temperatures and reduced rainfall, especially in the upper and middle part of the basins; processes of soil degradation resulting from the intense ravine and planar erosion, subsidence of loess rocks, water logging and raising water table of groundwater;
- increase in the frequency and intensity of the steamy fog around the reservoir which forms due to difference between ambient temperature and temperature above water in cooling pond;
- intensive alga blooms and, consequently, occurrence of fish mortality due to the reduced oxygen content in water, slow water exchange and the formation of stagnation zones;
- intensification of river pollution during the low water level periods – due to wastewater discharges by municipalities and industries without the adequate treatment, inefficient treatment plants or no treatment.

The increased irreversible losses of water and the reduced water volume of watercourses with a gradual temperature increase and rainfall decrease are observed in Ukraine. The answer to this challenge should be a change in the attitude to water: maximum economy, adequate pricing, termination of pollution, groundwater use, maximum treatment and swivel water use, recovery of the natural rivers, lakes, flood plains, deltas, coastal zones, swamps and wetlands, the reduced surface area of reservoirs. Accordingly, the adequate revision of the Water Code, and the national strategies in water management, education of water users and sustainable water consumption. Ratification of the Protocol on Strategic Environmental Assessment introduced the new legal instrument to be applied *inter alia* to the water management schemes and plans. The necessary revision of the draft law on Environmental Impact Assessment, its expert discussion and approval by the Verkhovna Rada of Ukraine currently shall be accelerated in Ukraine to fully extent address to water saving issue in the each investment project.

References

1. Boychenko S., Voloshchuk V.: The stochastic semi-empirical model of space-temporal transformation of the modern climate of Ukraine. *Ann. of the National Academy of Science of Ukraine*, 1, 105–109, 2007. http://www.nbuv.gov.ua./portal/all/repotrs/2007-01/07-01-20.pdf

2. Boychenko S.: Semi-empirical models and scenarios of global and regional changes of climate. Kyiv, Naukova Dumka 2008.

3. Boychenko S.: Features of climate change and consequences for Ukraine. *Climate Change, environment and modern city*. 2015. http://www.ukma.edu.ua /index.php/news/2117-konferentsiia-zminy-klimatu-navkolyshnie-seredovyshche-ta-suchasne-misto

4. Climate change 2013: The Scientific Basis – Contribution of Working Grup1 to the IPCC Third Assessment Report, UNEP/WMO. https://mail.google.com/mail/u/0/#inbox/15077c17caf59bc4

5. DEFRA: News from DEFRA – August 2010. http://archive.defra.gov.uk/environment/climate/documents/interim2/acc-news-1008.pdf.

6. Europe Adapts to Climate Change: Comparing National Adaptation Strategies. http://www.peer.eu/publications/europe-adapts-to-climate-change/

7. European Commission: Adaptation to climate change. http://ec.europa.eu/clima/policies/adaptation/documentation_en.htm

8. European Commission: Climate strategies & targets. http://ec.europa.eu/clima/policies/strategies/index_en.htm

9. Feyen L., Dankers R.: Impact of global warming on streamflow drought in Europe. *Journal of Geophysical Research* 114, D17116, 2009.

10. New M., Perker D., Mattin S., Rigir I.: Surface air temperature and its changes over the past 150 years. *Reviews of Geophysics*, 37, 173-180, 1999.

11. Kobak K., Kondrashova N.: Global warming and nature zone. *Meteorology and climatology*, 8, 91–97, 1992.

12. Oliver J. E., Fairbridge R. W. (eds.): The Encyclopedia of Climatology. The Encyclopedia of Earth Sciences. New York: van Nostrand Reinhold, 1987.

13. Tkachenko V., Boychenko S.: Structural drift of phitosystems steppe of Ukraine under influence of climatic changes and scenarios for first half XXI centure. *Ann. of the National Academy of Science of Ukraine*, 4, 172–180, 2014.

14. Velichko A.: Stability of a landscape environment and it bio- and a geovariety in view of dynamics latitude values. *Izvestia AS RF Geography*, 5, 7–21, 2002.
15. Voloshchuk V.: Semi-empirical statistical models of seasonal and geographic distribution of precipitation in the territory of Ukraine. *Proceedings of Third International Conference on Water Resources and Environment Research (ICWRER)*, 3, 224–229, Germany 2002.
16. Voloshchuk V., Boychenko S.: Scenarios of possible changes of climate of Ukraine in 21 century (under influence of global anthropogenic warming). *The Climate of Ukraine*, 308–331, Kiev, Raevsky 2003.
17. Voloshchuk V., Boychenko S., Stepanenko S, Trofimchuk A.: Semi-empirical scenarios of possible global and regional ecological consequences associated with further global warming. *A Gateway to Sustainable Development. Proceedings of the 30th International Conference Pacem in Maribus*, 624–635, Kiev – Sevastopol, 2004.
18. Voloshchuk V., Boychenko S.: The semi-empirical model and scenarios climate changes (global and regional aspects). *Global and Regional Climate Changes*, Ukraine, Kyiv 2010. http://www.uhmi.org.ua /conf/climate_changes/presentation_pdf/oral2/Voloshchuk_Boychenko.pdf
19. Державна служба статистики України: Про використання води в Україні та регіонах у 2014 році. *Статистичний бюлетень*, Київ 2015.
20. Державна служба статистики України: Довкілля України. *Статистичний збірник за 2013 рік*, Київ 2014.
21. Міністерство регіонального розвитку, будівництва та житлово-комунального господарства: Національна доповідь про якість питної води та стан питного водопостачання в Україні у 2013 році. http://www.minregion.gov.ua/zhkh/pitna-voda-ta-pitne-vodopostachannya-vodovidvedennya-teplopostachannya-502164/
22. Національний інститут стратегічних досліджень: Аналіз актуальних чинників погіршення якості питного водопостачання в контексті національної безпеки України. *Аналітична записка*. http://www.niss.gov.ua/articles/1037#_ftnref1

Processing Technologies of Technogenic Waste into Filter Media for Sewage Treatment of Industrial Objects

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Abstract

Number of technogenic waste from industrial facilities that affect the environment pollution is discussed in the article. Research of recycling slag and sludge materials by converting them in high temperature showed that the ratio of slag and sludge water purification affect to properties of carbon-mineral materials which were explored as filtration media in the purification process of wastewater. Materials are efficient in waste water treatment processes through wastewater purification degree from oil impurities as in the preliminary and final filtering after thin-layer tank rises to 70.4–89.1%, which reduces water pollution. Under similar experimental conditions the degree of purification from suspended particles ranged from 84.1 to 89.9%. Slag and sludge disposal, utilization of these waste materials and their use in water treatment tends to reduce pollution and increase environmental security in the region.

Keywords

environment, utilization, toxic components, wastewater treatment technology, filtration, thin-layer tank, water purification degree

1 *Introduction*

Sustainable development of society is closely connected with ecological safety (*Pawlowski, 2012*]. It is mainly ecologic threats caused by pollution of environment, which is tended by three main factors – the accumulation of man-made (technogenic) waste, pollution of the hydrosphere and atmosphere. The greatest share of waste is characterized by power engineering – slag-ash materials of thermal power plants (TPP). According to 2014 year statistical data (*Prokopenko, 2015*), in the Ukrainian dumps of TPP heaps of mines, tailings pond and a sludge were accumulated 30–33 billion tons of industrial solid waste, which is about 101.2 tons for 1 person, and annually produce about 448.1 million tons (only 10–15% are used in building construction). The industrial facilities of mining, petrochemicals and car-electronic-engineering produce large quantities of water treatment sludge's

– about 924 tons per year in the cleaning process. Influence of technogenic waste on the environmental safety of the region was presented in (*Adamenko et al., 2007*). In publications (*Krivenko et al., 2012; Kumar, 2009; Uretski et al., 2015; Chelyadyn et al., 2006; Zapolskiy et al., 2000*) the technology of processing slag and sludge waste as energy systems, which are quite expensive and complex. Known methods and equipment for wastewater treatment (*Wanga et al., 2015; Cloete et al. 2010; Gehrke et al., 2015*) are not effective in terms of decontamination of hazardous components (55–75% degree of purification), which leads to further pollution of the hydrosphere and lowering the environmental safety of the region.

Thus reducing the amount of pollution coming from industrial facilities into the environment through the development of new technologies of processing slag, ash and mud and by improving the methods and tools of water treatment can reduce the number of man-made pollution, which will increase the level of environmental safety of objects, region and Ukraine in general, and therefore is an urgent problem today that have ecological, social and economic importance.

2 *Materials and Methods*

The methodology of the research methods of high-temperature disposal of technogenic wastes includes the following steps: eduction of the optimal composition of the mixture on the basis of physical and chemical composition (TPP slag, sludge purification of waste water and other components), that dispersed, mixed in certain proportions, granulated and heat treatment, which was carried out at a temperature of 400, 500, 600, 800 and 1000°C for different times in a muffle furnace. With the device "Q-1000" (MOM, Soviet Union) investigated the thermodynamics of the formation of carbon-mineral materials CMM, and their phase composition was determined using X-ray diffraction on the diffractometer DRON-2.0 (BOUREVESTNIK INC., Russia). Specific surface of CMM received was determined using a chromatograph analyzer "Gemini", (Micromeritics, USA), defined porosity and strength of physical and mechanical tests according to DSTU B V.2.7-114-2002 and GOST 101-80.

Cleaning the water by filtering was performed on two fractions of CMM: I – column loaded with grain size fraction 2–5 mm and II – 5–7 mm, which received us with slag sludge. Filtering was conducted in different directions of the flow of waste water. The degree of purification of α determined as percentage of C / C_0, where C – concentration contaminant after purification and C_0 concentration contaminant before purification. The content of harmful components determined by methods described (*Plappally, 2010*).

Research on pretreatment of wastewater city by filtration through different CMM performed until slippage of suspended particles in the filtrate (purified water) granules through CMM size: 3–5 mm (samples 1, 4, 7); 6–8mm (samples 2, 6, 8) and 9–15 mm (samples 3, 5, 9) and the direction of water flow: from the bottom up (A), from top to bottom (B), from left to right (C).

For article investigation we use CMM described above and prepared as in publications (*Zapolskiy et al., 2000;* Kulskyy *et al., 1980; Chelyadyn et al., 2007*) that shown the effectiveness of such modified materials.

The methodology of this research similar to that described above (CMM filtration through different factions: 1 – faction column loaded grain size of 5 mm, and 2 – fraction grain size up to 7 mm. Filtration was carried out in two directions of water flow – from the top down and bottom up.

In the third stage, we research on improving the efficiency of field water purification JSC "Precarpathian management of drilling operations" to indicators that are standardized to pump them into the reservoir to maintain reservoir pressure, which reduces filter zone mudding hole and corrosion of pipes and equipment. The study included a cleaning method that provides for the separation of solids in sedimentation tanks with inclined plane and reservoir water followed by filtration through CMM.

3 *Results and Discussion*

It is known that ash-slag materials of TPP contain mostly SiO_2, Al_2O_3 and Fe_2O_3 (Table 1), water treatment sludge of mining industry – mechanical impurities; organic matter (oil, flocculants); Aluminum hydroxide and iron hydroxide formed from coagulants, and hydroxides of other metals. For the environment is especially harmful sludge of electronic engineering industries, containing hazardous concentrations of toxic metal ions – Chrome, Zinc, Copper, Nickel, Cadmium and others heavy metals that formed in the purification of electroplating wastewater.

Table 1. The composition of techogenic materials

Components [wt. %] / Name of waste	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	H_2O and other
Sludge	2.8	9.7	48.2	4.8	2.8	3.7	28.0
Ash	59.0	21.7	9.0	3.7	1.6	2.8	2.1
Slag	54.8	21.3	17.4	2.3	1.3	0.8	0.1

The said composition of the ash of thermal power plants and water treatment sludge indicates the possibility of processing in the ceramic material (*Chelyadyn et al., 2006*) which depending on the ratios of the components of the charge and receives certain parameters of technology indicators.

As harmful components and humidity in the test ash-slag and sewage sludge significantly differs that matched shown in our research (*Zapolskiy et al., 2000*) and other sources of information (*Wanga et al., 2015*), we identified two main areas of research for the development of processing technologies in following areas:

1. High-temperature treatment (600–850°C) – utilization of slag and sludge throught converted toxic components into new carbon-mineral materials (CMM), which are not harmful to the environment and can be used in processes of water gas purification.

2. Low-temperature area (20–200°C), in which transform slag, ash and sludge that containing toxic components in small amounts (within acceptable health standards), but because the technology is less energy-consuming, and the resulting safe materials that can be used in the construction industry.

This publication shows the results of research on high-temperature technology to produce materials for water purification processes. The main indicators of process water purification materials used in filtration and adsorption (10) are strength, porosity and surface area.

Theoretical and experimental studies to obtain ceramic porous materials indicate that their strength and porosity affects the composition of components of the charge and, in particular, the ratio of Silicon oxide, Aluminum and Iron compounds (*Gehrke et al., 2015; Plappally, 2010; Kulskyy et al., 1980; Chelyadyn et al., 2007*).

Physical and chemical nature of the proposed high-technology waste management is as follows. During the heat treatment there are two conversion: components physical transformation (change of viscosity and plasticity) and chemical transformation (oxidation, interaction) of raw mixture in a non-toxic nickel, copper and chrome ferrites (*Chelyadyn et al., 2012*). Oxidation of organic matter in a closed volume mixture of lack of oxygen leads to the formation of carbon in the ceramic material. Result of physical and chemical transformations components of the charge pellet form new carbon-mineral materials with ferrite on its surface (*Kempf, 1990*).

To establish the physical and chemical parameters of prepared CMM was conducted appropriate studies. For example, by thermal analysis of the CMM formation indicates that the transition of hydroxide slurry in alumina-silica ceramics is endothermic process and the structure of connected pores characterized by irregular shape, with the number of isolated pores are very small. X-ray analysis of the obtained samples showed the presence in CMM surface ferrite spinels of Ni, Cr and Cu. Physical and chemical properties of CMM granules obtained depending on the ratio of slag and sludge summarized in Table 2.

Based on the research results we obtained a patent (*Zapolskiy et al., 2000*). Implementation of one of the proposed processing technology of TPP slag and slurry of mining and petrochemical facilities helps to reduce the amount of man-made materials and harmful components. It's 50–60 ths. tons per year.

Table 2. Physical and chemical properties of CMM formed granular

№ samples	Interrelation of slag: sludge	Sorption [%]	Open porosity[%]	The average density [g/cm^3]	Specific surface [m^2/g]
1	3.5:1	19.0	33.5	1.62	18.1
2	2.5:1	16.6	32.1	1.83	20.5
3	4.0:1	20.4	35.1	1.78	16.8
4	2.5:1	13.6	26.7	1.74	14.5
5	1.5:1	13.8	24.1	1.83	12.0

In paper (*Chelyadyn et al., 2012; Adamenko and Prykhodko, 2000*) we described that environmental impact in Carpathian region caused by waste water industrial facilities, namely: JSC "Naftokhimik Prykarpattya" (Nadvirna city, Ivano-Frankivsk region), Collective Enterprise "Ivano-Frankivsk-Water-Eco-Tech-Prom" (Ivano-Frankivsk city) and JSC "Precarpathian management of drilling operations" (Dolyna city, Ivano-Frankivsk region). At these facilities waste waters transform using biological methods, based on the processes of nitrification-denitrification and are characterized by the fact that the degree of cleaning is reduced at low temperatures, and is necessary for a significant number of pollution or ingestion of toxic components in the wastewater, which affect bacteria process, add supplements to their activities.

The processes of biological wastewater treatment in the digesters, which are used in most industrial facilities, are energy intensive because large cost electricity to supply oxygen (air) that is used by 20–30%, occupy large areas and with the increase in energy prices is a biological treatment process economically unreasonable (*Klimenko et al., 2013*).

Monitoring the quality of sewage from Ivano-Frankivsk, which enter into water cleaning by CE "Ivano-Frankivsk-Water-Eco-Tech-Prom" and then dumped into the Bystrytsia River shown that they are not treated. For example, maximum allowable concentration (MAC) is 1.2–1.5 by chemical oxygen demand (COD). This is not effective enough work of pollution control facilities by bio-chemical water treatment (BCT), and excess of other harmful components (heavy metals) that not be reduced by this method. We therefore conducted a study of their treatment prior to admission to the BCT.

In the first phase of research on wastewater treatment of CE "Ivano-Frankivsk-Water-Eco-Tech-Prom" laboratory experiment was performed using model and industrial samples of waste water of various enterprises by without or with the addition of coagulants filtration on a laboratory setup that included filtering columns, which were CMM loaded granules.

The research results of purification by filtration through CMM is given in Table 3.

Table 3. Indicators wastewater before and after treatment

No samples	Indicators of CMM		Water for cleaning [mg/dm^3]		Water after cleaning [mg/dm^3]		The degree of purification (α) [%]	
	Faction [mm]	Porosity [%]	Suspension	Ammonium Nitrogen	Suspension	Ammonium Nitrogen	Suspension	Ammonium Nitrogen
1	3–5	82	28.2	5.0	3.6	0.2	87.2	96.0
2	6–10	89	28.2	5.0	3.9	0.15	86.2	97.1
3	11–15	92	28.2	5.0	4.1	0.25	85.5	95.4
4	3–5	81	23.6	4.6	3.0	0.15	87.3	96.7
5	6–10	88	23.6	4.6	3.3	0.11	86.0	97.8
6	11–15	93	23.6	4.6	3.2	0.21	86.4	95.6
7	3–5	83	25.3	6.4	3.5	0.45	86.2	91.5
8	6–10	87	25.3	6.4	3.7	0.52	85.4	92.5
9	11–15	94	25.3	6.4	3.8	0.55	85.0	96.2

According to the results of these studies filter cycle (until slippage contaminant) cleaning depends on the direction of the water and the size of the pellet loading in filter columns. The direction of the flow of waste water in the process and the change in pressure at the inlet of the filter in different ways, namely increases significantly if the flow is directed downward, and the least – for horizontal filtering.

Results of city wastewater treatment pilot plant by the previous filtering through CMM indicate partial decrease of COD, suspended particles, ions Chromium (VI) and surfactants. According to the research we found that the degree of purification of waste waters from suspended particles in the waste water through CMM filtration leads to reduction of suspended particles in the treated water (80–85%), COD 50–60%, which reduces the load on the steps of purification (physicochemical and biological), reduces levels of metals (Zn, Cr and Fe), which are environmentally hazardous to water bodies. Reduction of metals is important because water from rivers is often used for drinking water supply of settlements.

In the second phase of research to improve the sewage of JSC "Naftokhimik Prykarpattya" by oil impurities (o/i) in a laboratory setting, able to bear that filtering column and thin-layer tank, using real and model waters. Average chemical composition of the reservoir wastewater characteristic Precarpathian oilfield region is next (mg/l): SO_4^{2-} 80.40–120.24; Cl^- 81.3–320.4; HCO_3^- 12.0–18.9; Ca^{2+} 112–548; Mg^{2+} 42.0–45.6; $K^+ + Na^+$ 38.1–60.2; o/i 12.6–40.3; mechanical impurities (suspended) 15.3–60.1; and pH 6–7. The results are given in Table 4.

Table 4. Indicators of reservoir water in different directions filter

Type of CMM	Sample formation water	The content of ingredients before cleaning [mg/dm^3]		Filtration top-down after cleaning [mg/dm^3]				Filtration bottom-up after cleaning [mg/dm^3]			
		o/i	suspension	o/i	suspension	α n/a [%]	α susp. [%]	o/i	suspension	α o/i [%]	α susp. [%]
1 column diameter fraction Ø (2–4)	1	12.6	15.3	2.5	5.1	80.2	66.6	2.1	5.2	83.3	66.9
	2	15.3	20.6	3.6	6.3	76.4	69.4	3.0	6.4	80.4	68.9
	3	18.2	35.3	4.2	7.2	76.9	79.6	3.8	6.9	79.1	80.6
2 column diameter fraction Ø (5–7)	1	12.6	15.3	3.6	6.4	71.4	58.2	2.5	6.4	80.2	70.6
	2	15.3	20.6	4.0	7.1	73.9	65.5	3.3	6.8	78.4	69.8
	3	18.2	35.3	5.1	7.5	71.9	79.3	3.9	7.0	78.6	80.2

Results of reservoir water cleaning showed that the degree of purification of waste water by filtering through CMM rises to 66.9–80.6% for suspended and until 78.4–83.3% for o/i, and on their basis improved construction of the filter-adsorber (*Chelyadyn et al., 2005*) which works effectively in the treatment of wastewater by filtration (implemented at the refinery) in the direction of flow from top to bottom. Automatic washing sludge from water purification filter load in such a filter in the direction of the water flow upward in achieving fill the pores of the filter material layer mechanical pollution and its adsorption capacity for certain toxic pollution, makes it possible to automate the process of filter (filter-regeneration). This provides continuity and block filter reduces staff.

Results of research third part are given in Table 5.

Table 5. Results of treatment of wastewater in the sump thin layer

Indexes / Sample waste water		The content of impurities in the water to clean [mg/dm^3]		Angle planes α [degr.]	The content of pollutants in the water after purification [mg/dm^3]		Degree cleaning [%]	
		suspended	o / i		suspended	o / i	suspended	o / i
1	refineries	7.61	10.52	0	2.81	4.62	43.0	45.6
2	refineries	7.61	10.52	30	1.51	2.19	84.1	76.1
3	refineries	10.3	6.35	45	1.85	1.05	82.7	83.5
4	refineries	8.78	7.41	60	1.63	2.16	81.5	89.1
5	oil and gas manage-ment	22.3	1.23	0	12.64	0.56	50.2	54.5
6	oil and gas manage-ment	21.4	0.95	30	2.15	0.32	89.8	70.4
7	oil and gas manage-ment	22.3	1.23	45	2.33	0.72	89.5	73.9
8	oil and gas manage-ment	18.7	1.12	60	2.21	0.28	88.2	75.0

Analysis of the results of the research shows that the most effective water reservoir can be cleaned using tanks with inclined planes, which allows to reduction the space for pre-treatment. Based on the results of studies on the impact of the major structural elements of thin layer settler on the degree of sewage treatment (*Chelyadyn et al., 2005*) developed an improved design (*Chelyadyn et al., 2007b*), which makes it possible by changing the inclination of the inclined planes affect the degree of sewage treatment depending on the number of suspended at the entrance to the sump. Integrated wastewater treatment technology we described in patents (*Zapolskiy et al., 2000; Chelyadyn et al., 2010*).

4 Summary

1. Investigated processing methods of technogenic waste, including ash and slag of thermal power plants and water treatment sludge, indicate that recycling allows its utilization to receive carbon-mineral materials in medium temperatures (300–800°C) and which are recommended to use as filtration and adsorption material.

2. The technology of wastewater treatment by separation more pollution in advanced thin layer sump by changing the inclination of the inclined planes, increasing the degree of sewage treatment depending on the number of suspended at the entrance to the tank, and the final process filtration and sorption of contaminants wastewater can be implemented via download from CMM to the required degree of cleaning for certain indicators.

3. The technology of sewage treatment, which includes separation of more pollution in advanced thin layer sump and process filtration and sorption of pollutants from wastewater via download from carbon-mineral materials is more efficient and less energy intensive compared to chemical oxygen demand because the equipment is placed on small areas exposed to automation, and therefore it should be used for small travel and municipal facilities and to develop a mobile version for use in emergency situations.

References

1. Adamenko O. M., Chelyadyn L. I., Chelyadyn V. L.: Environmental safety hydrosphere region and study of wastewater treatment and water treatment sludge disposal. *Eco-technologies and resource security*, 6, 28–32, 2007.

2. Adamenko O. M., Prykhodko M. M.: Regional ecology and nature resources. Talya, Ivano-Frankivsk 2000.

3. Chelyadyn L. I., Drohomyretska J. M., Chelyadyn V. L., Skrobach M. R., V. P. Nestor: The method of wastewater treatment and sludge processing. Patent number 28030, Ukraine, IPC C 02 F 3/24. The applicant and patentee number 200707243, appl. 27.06.2007, publl. 26.11.2007(b), Bull. Number 5.

4. Chelyadyn L. I., Drohomyretska J.M., Chelyadyn V. L., Skrobach M. R., Bohuslavets M. M..: The filter-adsorber. Patent number 27668, Ukraine, IPC B 01 D 35/02. The applicant and patentee number 200707240, appl. 27.06.2007; publ. 12.11.2007, Bull. Number 12.

5. Chelyadyn L. I., Khomyn V. R., Novosad P. V., Poznyak O. R.: Resource saving technologies of utilization of ash slag mixtures of thermoelectric power station and sludge of water purification. *Scientific Bulletin of UNFU*, 22 (13), 81–87, 2012. http://194.44.11.130/cgi-bin/irbis_nbuv/cgiirbis_64.exe

6. Chelyadyn L. I., Ligotsky M. V., Chelyadyn V. L., Rugytsky B. J.: Thin layer to clean water tank. Patent number 5740, Ukraine, IPC B 01 D 25/00. The applicant and patentee number 2004086748, appl. 12.08.2004, publ. 15.03.2005, Bull. Number 3.

7. Chelyadyn L. I., Mandryk O. M., Chelyadyn V. L., V. P. Nestor: Universal plant wastewater treatment and sludge processing. Patent number 48053, Ukraine IPC C 02 F 1/00. The applicant and patentee Ivano-Frankivsk National Technical University of Oil and Gas number 200907209, appl. 10.07.2009, publ.10.03.2010., Bull. Number 5.

8. Chelyadyn L. I., Novosad P. V, Chelyadyn V. L., Condur T. I.: A method for producing carbon-mineral materials. Patent number 13742, Ukraine, IPC C 02 F 3/24. The applicant and patentee number 200509909, appl. 21.10.2005, publ. 17.04.2006, Bull. Number 4.

9. Cloete T. E., de Kwaadsteniet M., Botes M. and López-Romero J. M. (eds.): Nanotechnology in Water Treatment Applications. Caister Academic Press 2010.

10. Gehrke I., Geiser A., Somborn-Schulz A.: Innovations in nanotechnology for water treatment. *Nanotechnology, Science and Applications*, 8, 1–17, 2015.

11. Kempf H.: Des ferrites absorbantes a partir de dechets toxiques. *Usine Nouv.*, 2274, 1990.

12. Klimenko N. A., Grechanik S. V., Bezpoyasko V. A., Savchina L. A.: Improving the efficiency of water purification using activated carbons with improved sorption characteristics. *Chemistry and Technology of Water*, 6, 470–481, 2013.

13. Krivenko P. V., Pushkarev K., Baranovsky V. B.: Building Materials: Textbook. Publishing Lyra-K, 2012.

14. Kumar V.: Physicochemical properties of fly ash from thermal power station and its effect on vegetation. *Global Journal of Environmental Research*, 3 (2), 102–105, 2009.

15. Pawlowski L.: Do the liberal capitalism and globalization enable the implementation of sustainable development strategy. *Problemy Ekorozwoju*, 7 (2), 7–13, 2012.

16. Plappally A. K.: Theoretical and empirical modeling of flow, strength, leaching and micro-structural characteristics of V shaped porous ceramic water filters. Ph.D. Dissertation, The Ohio State University, Columbus 2010.

17. Prokopenko O. (ed.): Statistical Yearbook. Environment of Ukraine 2014. State Statistics Service of Ukraine, Kyiv 2015.

18. Uretski E. A., Gazizov R. T., Moroz V. V.: Alternative technology galvanic waste, contaminated with organic and mineral ingredients paint industries in the production of building materials. *Вестник Брестского государственного технического университета. Водохозяйственное строительство, теплоэнергетика и геоэкология* 2 (92), 62–65, 2015.

19. Wanga H., Shen S., Liu L., Ji Y., Wang F.: Effective adsorption of phosphate from wastewaters by big composite pellets made of reduced steel slag and iron ore concentrate. *Environmental Technology*, 36 (22), 2835–2846, 2015.

20. Zapolskiy A. K.: Physical and chemical bases of technology of sewage treatment. Libra, 2000.

Application of an electronic nose for odour nuisance evaluation of wastewater treatment plant devices

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Abstract

The treated wastewater which is discharged from a treatment plant should meet the requirements established in the legal standards of a given country. These mainly include the permissible levels of such parameters as Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), the concentration of nitrogen and phosphorus compounds pH, Total Organic Carbon (TOC). Another important parameter that should be taken into account is odour nuisance of wastewater.

The methods of assessing a smell nuisance of wastewater are described in the article. There are also presented measurements of odour concentration in the SBR laboratory bioreactor using a calibrated gas sensor array (e-nose). Two measurement devices were used as an information source regarding the presence of smell nuisance gases: an array consisting of 8 MOS-type gas sensors and a dynamic olfactometer. The research covered the stage of a normal bioreactor performance and simulation of the aeration system failure. With the gas sensor array, a static response has been recorded for air samples above the surface of treated wastewater.

Presented example of electronic nose application shows that continuous monitoring of sewage parameters yields information about the parameters of treated wastewater, thus enabling to obtain the data pertaining to the odour nuisance and the processes occurring in the reactor chamber. However, there are still no commercially-available devices which could be used for continuous measurement and control. The estimated data could prove electronic nose to be valuable tool in early warning system within devices of wastewater treatment.

Keywords

E-nose, wastewater treatment plant, odour nuisance

1 Introduction

Dynamically developing economy necessitates monitoring of air quality and detection of situations when the pollutants exceed permissible levels. Moreover, the growing awareness of social rights increases the number of complaints filed to the related institutions, predominantly pertaining to odour nuisance. Thus far, no legal regulations have been established in Poland and Ukraine, which would set the permissible odour concentration in the vicinity of emission sources. Currently, act concerning prevention of odour nuisance is underway in Poland. When the act enters into force, the number of expert evaluations performed in order to determine the level of nuisance of volatile air pollution emission sources will arise. Therefore, constant development of methods which enable an accurate evaluation of volatile air pollutants could be employed – for instance – on wastewater treatment plant premises, is necessary. However, there is still no complete system of continuous and automatic assessment of malodorous air parameters, especially the odour concentration.

Due to the unpleasant smell of WWTP devices, actions are taken to mitigate the emission of odorants into the environment. Treatment plants increasingly often invest in hermetization of the devices with greatest odour-generating potential. In such a solution, malodorous air is treated in various types of filters and biofilters. Despite this, the wastewater treatment can be considered as one of the emission sources of gaseous air pollutants which cause the greatest nuisance. Each wastewater treatment process, especially connected with anaerobic conditions, emits odour-active compounds. Generally, the sources of air pollutants in a wastewater treatment plant can be divided into two classes: i) places with high wastewater flow rate, occupying large area, e.g. holding or equalization tanks, and ii) places in which new odour-active compounds are created. These mostly include the inflows of raw wastewater and places connected with sewage sludge and screenings processing. Surveys conducted in Germany among the technical staff of 100 wastewater treatment plants confirm that the main source of air pollution includes the processes connected with initial treatment, primary sedimentation tanks, and processing of sewage sludge (*Gostelow et al., 2001*). The level of olfactory concentration at a wastewater inflow and mechanical treatment part may equal 30–1000ou_E/m^3, whereas the biological treatment may generate 5–120 ou_E/m^3, and finally the sludge processing yields 100–1000000 ou_E/m^3.

Wastewater is a source of numerous volatile organic compounds and no instrument is able to accurately identify and determine their concentration or – even more so – the synergic influence on olfactory concentration (*Hobbs et al., 1995*). These mainly include sulfur of nitrogen compounds, organic acids, aldehydes and ketones. Majority of malodorous compounds is presented in Tab. 1.

Table 1. Malodorous compounds related with operation of a wastewater treatment plant (*Bonnin et al., 2011; Brennan, 1993; Gostelow et al., 2001; Metcalf and Eddy, 2004*)

Class	**Compound**	**Type of odour**
Sulfur compounds	hydrogen sulfide	rotten eggs
	ethyl sulfide	nauseating, ethereal
	methyl sulfide	rotten vegetables, garlic-like
	dimethyl sulfide	unpleasant, burnt rubber
	diallyl sulfide	garlic-like
	carbon sulfides	rotten vegetables
	dimethyl sulfide	rotten
	methyl mercaptan	rotten cabbage, garlic-like
	ethyl mercaptan	rotten cabbage
	propyl mercaptan	unpleasant
	butyl mercaptan	unpleasant
	tert-butyl mercaptan	unpleasant
	allyl mercaptan	garlic-like
	crotyl mercaptan	skunk, rancid
	benzyl mercaptan	unpleasant
	thiocrestol	skunk, rancid
	thiophenol	rotten, nauseating, decomposing
	sulfur dioxide	pungent, irritating
Nitrogen compounds	ammonia	pungent, irritating
	methylamine	fish-like
	dimethylamine	fish-like
	trimethylamine	fish-like, ammonia-like
	ethylamine	ammonia-like
	diethylamine	fish-like
	trietyloamina	fish-like
	diamine, cadaverine	rotten meat
	pyridyna	unpleasant, irritating
	indole	fecal, nauseating
	skatole	fecal, nauseating
Acids	acetic	vinegar-like
	butanoic	rancid, sweaty
	valeric	sweet
Aldehydes and ketones	formaldehyde	irritating, choking
	acetaldehyde	fruity, apples
	butyraldehyde	rancid, sweaty
	isobutyraldehyde	fruity
	isovaleraldehyde	fruity, apples
	acetone	fruity, sweet
	butanone	green apples

The concentration levels of single dominant polluted air components, such as, e.g. hydrogen sulfide, can constitute an indicator of air odour nuisance (*Stuetz et al., 1998*). P. Gostelow (*Gostelow et al., 2001*) correlated the concentration of hydrogen sulfide from 17 wastewater treatment plants and in the range of 10^2–10^7 ou_E/m^3 the authors have obtained the relationship formula between the olfactory concentration and the concentration of hydrogen sulfide $c_{od}=38902 \cdot c_{H2S}^{0.6371}$ with the coefficient of determination $R^2=0.69$. On the other hand, the studies conducted by University of Hertfordshire, UK, in 10 wastewater treatment plants found no clear relation between the concentration of hydrogen sulfide in wastewater and the Threshold Odour Number (TON) in the ranges $0–4 \cdot 10^3$ and $0–4 \cdot 10^5$ ou/m^3 (*Stuetz et al., 1999a*).

Multi-sensor systems which imitate human olfactory sense, called electronic noses seem to be a supplementation for traditional techniques of odour nuisances estimation and good perspective for future development of online measurements. An electronic nose consists of several key elements: a set of low-selective gas sensors, a system of signal processing and a system of model recognition. The scientific literature contains description of studies on the use of an electronic nose on wastewater treatment plant premises. Most often, it consisted in evaluating the possibility of employing the aforementioned electronic nose systems for identification and classification of odours in relation to their place of origin in the treatment plant (*Nake et al., 2005; Capelli et al., 2008*), as well as the assessment of odour concentration in the analyzed air samples (*Stuetz et al., 1999; Littarru, 2007; Nicolas et al., 2012*). Moreover, in some studies an attempt of using the e-nose for estimation of standard wastewater pollution parameters (*Bourgeois et al., 2001*), such as BOD (*Stuetz et al., 1999a; Onkal-Edgin et al, 2005*), as well as COD, TSS, Volatile Suspended Solids (VSS), turbidity (*Dewettinck et al., 2001*). The assumptions were that the wastewater characterized by higher level of pollution should be distinguishable from the wastewater with lower level of pollutants. In view of these studies, an electronic nose can also serve as a system of early detection of chemical compounds which would be hazardous for the organisms operating in the biological part of the treatment plant. One example of such substances includes the derivatives of crude oil, which are poorly-biodegradable and may negatively impact the operation of the activated sludge, thus disrupting the treatment process in the plant. Taking into the account a broad range of potential types of pollutants, a system with multiple gas sensors is well-suited for such tasks. Attempts of odour classification were also made for municipal wastewater treatment plants and light industrial treatment plants using e-nose (*Onkal-Engin et al., 2005*). The studies involved collecting air samples from individual treatment processes: initial treatment, sedimentation tanks, biological treatment, and discharge of treated wastewater. In order to perform classification, 144 samples were taken. The analyses of signals from gas sensor arrays were carried out by means of neuron networks with 12 input neurons and two hidden layers of 12 neurons each. High correlation, reaching 0.99, was obtained for individual types of odours. More information about the application of an e-nose for the evaluation of wastewater parameters is presented in Tab. 2.

Table 2. Application of an electronic nose for the evaluation of wastewater parameters

Reference	**Electronic nose**	**Parameters**	**Results**
Dewettinck, et al., 2001	FOX3000 Alpha M.O.S.	COD, TSS, VSS, turbidity	Poor correlation between the electronic nose response and VSS (R=0.67), weak correlation with other parameters: CODtot (R=0.53) CODsol (R=0.36) TSS (R=0.52), turbidity (R=0.53)
Onkal-Engin et al., 2005	Neotronics Scientific Ltd. mod. D;	BOD, classification	classification of wastewater, correlation of electronic nose response with BOD
Stuetz et al., 1999b	Neotronics Scientific Ltd. mod. D;	BOD, classification	classification of wastewater, correlation of electronic nose response with BOD
Bourgeois et al., 2003a; Bourgeois et al., 2003b; Bourgeois and Stuetz, 2002	eNOSE 5000 ProSat	detection of pollutants	Real-time detection of unknown pollutants, intermittent or accidental disch`1arge
Nake et al., 2005	PEN2 Airsense; Cyranose 320	wastewater type discrimination	Discrimination between odour samples from different locations in WWTP
Stuetz et al., 1999a	Neotronics Scientific Ltd. mod. D;	odour concentration	Correlation between TON and electronic nose in range 125–781066 ou_E/m^3
Nicolas et al., 2012	5xEN; 6×MOS sensors	odour concentration	Assessment of odour nuisance in vicinity of WWTP using an electronic nose compared with meteorological data, correlation e-nose with odour conc. in range to 4000 ou_E/m^3
Littarru, 2007	Airsense PEN2	odour concentration	Correlation electronic nose with odour conc. 0–200 ou_E/m^3 (R^2=0.94), discrimination between different samples from biofilters
Capelli et al., 2008	EOS25, EOS28, EOS35;	classification, odour concentration	Classification with high accuracy R^2=0.95 (for samples 100–150 ou_E/m^3), high correlation (R^2>0.9) electronic nose response with odour conc. in range 20–80 ou_E/m^3

2 *Technical details of odour nuisance evaluation*

Gas chromatography is a very precise technique employed for qualitative and quantitative chemical analyses with the accuracy up to several ppb (parts per billion). However, the knowledge of the chemical composition of an odorous gas gives no information about the remaining parameters, such as odour nuisance. Currently, the only method used for evaluation of odour nuisance is dynamic olfactometry. The assessment in this method is performed by a team of selected testers; therefore, the outcome is a subjective opinion of the people conducting the test. Although the cost of laboratory instruments is significantly lower than in the case of chromatography, the conducted measurements are both expensive and time-consuming, as they require many hours of work. Additionally, in Poland there are few certified units which perform olfactometry measurements. The electronic nose is a very promising tool for evaluation of odour nuisance.

2.1. Electronic nose

An electronic nose imitates the human olfactory sense. Therefore, this device is not an objective substance detector. Each electronic nose comprises of an array of gas sensors (*Craven et al., 1996*). Every gas sample is characterized by combined signals from the sensor array. The possibilities of the same combination occurring in two different samples are extremely low; therefore, these signal combinations – due to their uniqueness – are frequently called *gas fingerprints* (*Wilson and Baietto, 2009*).

The principle of electronic nose operation makes it unable to accurately distinguish individual components of a gas mixture. The main objective is the identification of general properties of gases. Multi-dimensional, complex set of signals from all array elements is taken into account in the analysis. These signals can be correlated with numerous physicochemical parameters of gas mixtures. Such analyses enable measuring the concentration of chemical substances, total volatile organic compounds, odour concentration and other parameter of gas samples or even liquids in equilibrium with headspace gas phase. Such versatility of the device, coupled with relatively low price enables its application in many fields of science and branches of industry.

There are four groups of gas sensors which can be applied in an electronic nose: optical, thermal, electrochemical and gravimetric. The most common ones include the resistance and potentiometric electrochemical sensors.

2.2. Gas sensors

In order to be efficiently used in an electronic nose sensor array, gas sensors have to meet numerous criteria. They are checked in regard to the sensitivity to a given gas, selectivity, reaction time, signal recovery time or their lifespan. Moreover, power consumption is a key parameter as well to obtain full functionality of a device. The general properties of main groups of gas sensors are presented in Tab. 3.

Table 3. Physicochemical properties of gas sensors (*Arshak et al., 2003; James et al., 2004; Mielle and Marquis, 2000; Wilson and Baietto, 2009*)

Sensor	**Advantages**	**Disadvantages**
Calorimetric and catalytic sensors (CB)	Quick reaction, short signal recovery time, high sensitivity to oxidized compounds containing oxygen	High operational temperature, sensitive only to the compounds comprising oxygen
Catalytic (MOSFET)	Small sensor size, low measurement costs	Require controlling the environmental conditions, drifting base line, low sensitivity to ammonia and carbon dioxide
Conductive polymers	Low operational temperature, sensitive to many volatile organic compounds, quick reaction, various sensor, inexpensive	Susceptible to poisoning, sensitive to moisture and temperature, sensors may become overloaded by certain compounds, limited lifespan
Electrochem.	Low operational temperature, low power consumption, sensitive to many volatile organic compounds	Large sensor size, limited sensibility to simple compounds with low molar mass
Metal oxide semiconduct.	High sensitivity, narrow sensitivity range, very quick reaction and signal recovery time for compounds with low molar mass	High operational temperature, high power consumption, susceptible to poisoning with sulfur and weak acids, limited coating types, sensitive to moisture, inaccurate
Optical	High sensitivity, ability of distinguishing individual compounds in a mixture, can measure numerous parameters	Complex sensor arrays, expensive operation, vulnerable to mechanical damage, limited mobility
Quartz crystal microbalance (QMB)	Good precision, wide selection of the active element coatings, high sensitivity	Complex electronic circuits, weak signal to static noise ratio, sensitive to moisture and temperature
Surface acoustic wave sensors (SAW)	High sensitivity, good reaction time, inexpensive, small size, sensitive to all gases	Complex electronic circuits, sensitive to temperature

Considering the placement of sensors in relation to the gas stream flow direction, serial and parallel arrays can be distinguished. In a serial array, the stream flowing through the chamber flushes the sensors according to the order they were installed, which may cause distortions. On the other hand, in a parallel matrix sensors are usually arranged in a circle and the influent gas reaches each of them simultaneously (*Nakamoto, 2006*).

2.3. MOS-type gas sensors

One of the more popular sensors applied in electronic nose arrays are MOS-type sensors. The metal oxide semiconductor sensors have been developed since mid- twentieth century. Gas-sensitive properties of germanium oxide were described in 1953 (*Brattain and Bardeen, 1953*).

The first gas sensors were made of ZnO, and later such materials as SnO_2, TiO_2, WO_3, Ga_2O_3, In_2O_3 and Fe_2O_3 were employed for this purpose. Out of the afore-mentioned materials, the tin dioxide with grainy structure is the best known. It is characterized by a developed surface on which the phenomenon of adsorption/desorption occurs. Depending on the coating process, sensors are divided into thin-film sensors, in which the gas-sensitive layer is 5nm–2µm thick, and thick-film sensors with 10µm–300µm thick gas-sensitive layer. The thin-film gas-sensitive material is applied by spraying or vacuum deposition. On the other hand, in the case of thick-film sensors, the layer is created through the application of a paste containing metal oxides, and its subsequent firing. Thick-film sensors are less susceptible to poisoning, more durable and are characterized by higher sensitivity than the thin-film counterparts.

MOS sensors allow measuring the concentration of gases due to the change in the electric conductivity of the semiconductor receptor and transducer element. In MOS sensors, the measuring element usually constitutes sintered tin dioxide. Depending on the application, the sintered SnO_2 contains various additions, usually in the form of noble metals.

The change of the electric conductivity in semiconductor layer is a result of chemiosorption, i.e. creation of chemical bonds between the gas molecules and the semiconductor. This leads to a change in the concentration of current carriers on the surface of the semiconductor and thus, to a change in the electric conductivity. The creation of signal in a semiconductor is presented in Fig. 1. In such process, the adsorption site in oxygen vacancies of the surface layer of SnO_2 grains is relevant. The vacancies are point defects in the crystalline, consisting in that the lattice sites are unoccupied by atoms or ions. They constitute active centres, i.e. fragments of receptor and transducer element which participate in chemisorption of oxygen. Oxygen from air is bonded in vacancies (Fig.1a), which afterwards releases an electron from the semiconductor (Fig.1b). As a result, an electron-deficient surface layer is created, with electrons characterized by weak conductance (Fig.1c). Depending on the oxygen partial pressure and the temperature, equilibrium between the concentration of vacancies and oxygen will be attained. During the exposure of SnO_2 to the reducing gas, the reaction is reversed. Gas particles are bonded with oxygen atoms (Fig.1d). The covalent electron between oxygen and semiconductor returns to the semiconductor (Fig.1e), decreasing the electron-deficient surface, which results in an increase of conductance (Fig.1f). Due to the reaction of reducing gas with the adsorbed oxygen, molecules of such chemical compounds as CO, CO_2 or H_2O are created.

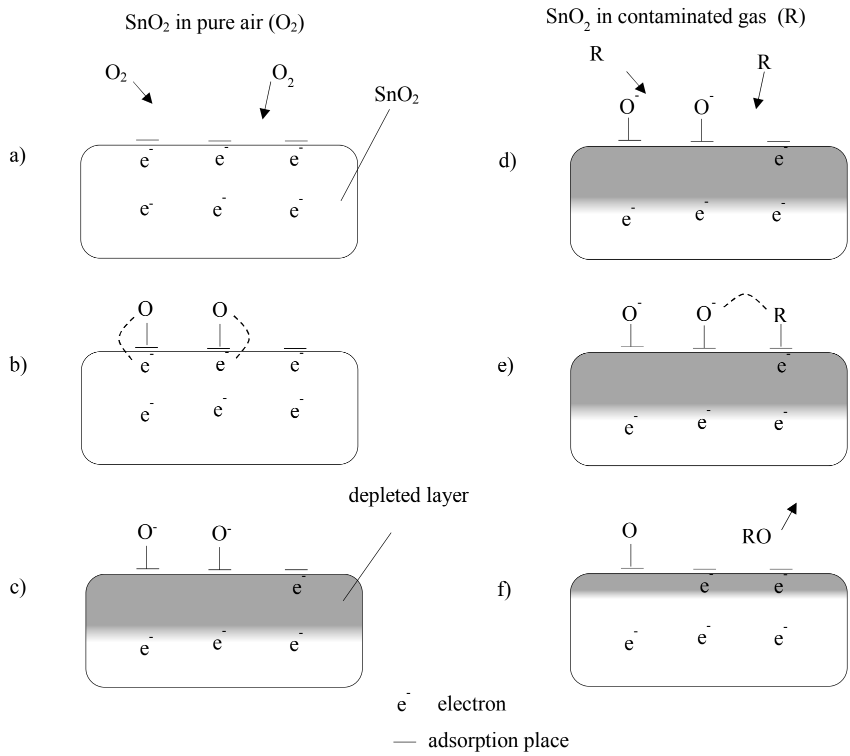

Fig. 1. Conductance change of SnO_2 as a result of ion exchange occurring in the air and reducing gas

Improvement of sensitivity and selectivity of sensors is carried out through (Teterycz, 2005):

- devising new gas-sensitive materials;
- modification of a sensor;
- uniform temperature distribution in the receptor;
- doping;
- incorporating a catalytic filter.

Utilizing catalysts with gas-sensitive material greatly improves the selectivity. Most frequently, these consist of noble metals, such as gold, palladium, platinum, and silver. The improvement of sensor sensitivity by means of doping is described by two models: chemical and electric.

The chemical model assumes that increased dissociation of oxygen or hydrogen occurs on the surface of catalysts (Fig. 2a). The catalyst increases the number of dissociated molecules, simultaneously lowering the energy required to dissociate the gas molecules. In an electrical model (Fig.2b) the grain conductance is influenced by the contact of the catalyst and grain surface. Partially oxidized metallic catalyst binds electrons from the semiconductor, which increases the width of the deficient layer.

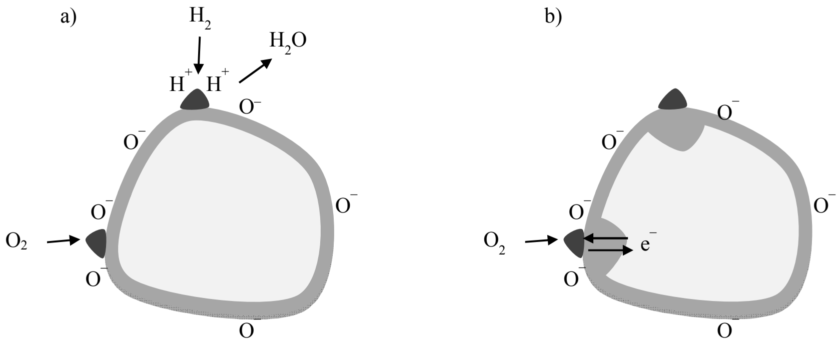

Fig. 2. Impact of doping: a) chemical , b) electrical

The phenomenon of electric conductivity change, depending on the concentration of reducing gas mixtures is complex and is influenced by numerous factors. Therefore, empirical formulas in which the electric conductivity change R_S is dependent on the concentration of reducing gases are elaborated, for instance it can be mentioned:

$$R_S = Ac^{\alpha} \tag{1}$$

where: A – constant, c – gas concentration, α – slope of the curve R_S.

If the resistance of a sensor in the gas is known, it is possible to read the gas concentrations using the characteristics supplied by the producer. An exemplary characteristic of TGS 2602 sensor made by Figaro Engineering is presented in Fig. 3. This sensor was designed for volatile organic compounds (VOC) detection. The coefficient on Y-axis is defined as R_S/R_O, where R_S – measured sensor resistance [Ω], R_O – sensor resistance in helium with the concentration of 100 ppm [Ω].

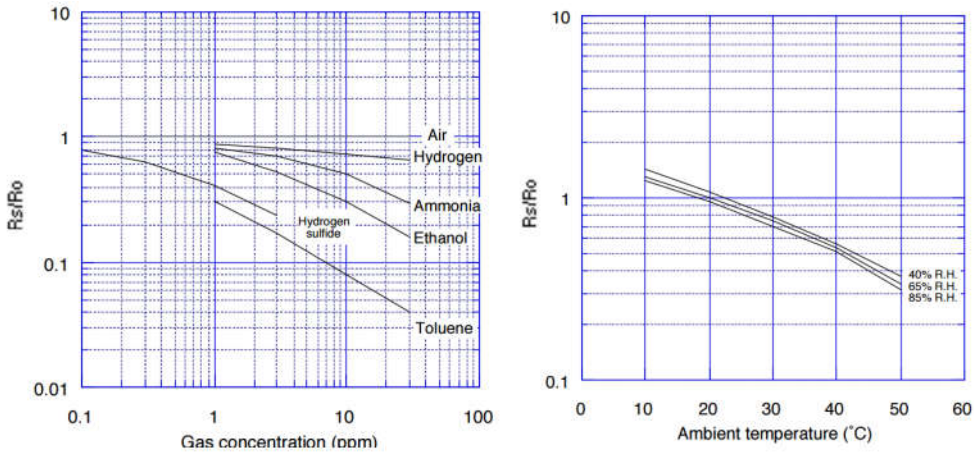

Fig. 3. TGS2602 sensor characteristics (www.figarosensor.com, 2016)

In oxide sensors, the thin-film layer and semiconductor with low mechanical durability is applied onto a ceramic base, and subsequently fired at a temperature of 970–1270 K. The base constitutes a pipe with the inner diameter of 1mm or a alundum plate (Al_2O_3), which is characterized by a very good thermal conductivity (20W/(m·K)). A heating spiral with the resistance amounting to several dozen ohms is placed inside the pipe or on the bottom layer of the plate. Metallic electrodes (either Au or Pt) are sprayed at both ends of the ceramic pipe, which enables electrical connection of a semiconductor. The entire sensor is placed in housing and covered with a metal mesh which disperses the stream of gas and simultaneously protects from the ignition of a combustible gas.

3 Processing of measurement data

The measurements conducted with MOS sensors array can be conducted with the following methods:

- static analysis of sensor reaction;
- dynamic analysis of sensor reaction.

The analysis of data from an electronic nose requires and initial processing of the measurements. In the case when the reaction of sensors to the gas with constant concentration (static response) is considered, it is possible to designate the resistance change ΔR of individual sensors, which is most often expressed as a difference (2), relative value (3), relative difference (4), and logarithmic relative value (5):

$$\Delta R = R_S - R_O \tag{2}$$

$$\Delta R = R_S / R_O \tag{3}$$

$$\Delta R = (R_S - R_O) / R_O \tag{4}$$

$$\Delta R = \ln(R_S / R_O) \tag{5}$$

where: R_S – sensor signal in a given time t, R_O – base line, sensor signal for carrier gas (*Distante et al., 2002; Gutierrez-Osuna, 2002*). The minimalisation of the sensor signal drift in time is an important advantage of correction.

In the case when the reaction of sensors to pulse dosed gas samples is considered, it is possible to designate additional attributes connected with characteristic properties of signal shape. Such properties may include the full width at half maximum, kurtosis, impulse area or skewness (*Brudzewski and Ulaczyk, 2009*). The rate of adsorption and desorption is different for individual gases, which may provide additional information about the examined samples.

3.1. Analysis of multi-dimensional data

The gaseous profiles from a sensors array are multi-dimensional and have to be analyzed by means of model identification systems, such as the Principal Component Analysis (PCA), Cluster Analysis (CA), Partial Least Squares method (PLS), Factorial Discriminant Analysis (FDA), Canonical Discriminant Analysis (DA), Hierarchical Clustering (HC) or Artificial Neural Network (ANN) (Schaller, Bosset and Escher, 1998). In the related literature, PCA and ANN methods are used most often for analyzing signals obtained by means of an electronic nose. According to some authors, ANNs are more efficient in classification and predictions of complex non-linear sets of data than multi-dimensional analysis methods (*Gardner and Bartlett, 1994; Haugen and Kvaal, 1998; Llobet et al., 1997; Schaller et al., 1998*).

3.2. Principal Component Analysis

PCA technique is based on formulation of new uncorrelated variables (axes) which in the greatest possible degree describe the variability of the analyzed dataset (*Krzanowski, 2000*). Principally, the designated new variables have no strictly physical significance; therefore have no unit. The only value which is marked is their input into the total dataset covariance, given as a percentage. However, they are presented in such a way that the differences and relations between the data, which are hidden within multi-dimensional datasets, become apparent. Hence, it is possible to group the measurement data. Additionally, PCA allows reducing the number of dataset dimensions, losing only small part of data in the process. The results can then be presented as graphs. Quite often, only 2 or 3 new PC variables describe as much as 90% of variables in a dataset; in such a case, graphical visualisations in the form of two- or three-dimensional graphs can be applied. In view of the above, PCA can be treated as a method of data compression which enables reversal of transformations, i.e. obtaining original measurement data from the space of principal components.

PCA algorithm is divided into the following stages: (i) creating matrix A out of the designated attributes (A), (ii) designating the matrix of centered values – by subtracting arithmetic mean of each column's element from each element of a given column, (iii) designating correlation or co-variance between individual attributes (dimensions), (iv) creating the matrix of co-variance, (v) designating eigenvalues of co-variance matrix, (vi) designating eigenvectors, which constitute directions of a new coordinate system that presents measurement data in such way so as to expose their variability (co-variance).

Eigenvectors matrix coupled with the eigenvalues matrix are a 'key' of transformations between the space of multi-dimensional data and the space of principal components.

In the case of statistical analysis of sensor response, the number of dimensions is usually equal to the number of sensors, and in the case of dynamic analysis, additional attributes connected with the signal shape features are included in the sensor response. All attributes must be standardized beforehand.

PCA algorithm starts with creating a matrix of the designated attributes (here called ***A*** – short for 'attributes') where the index *i* denotes the attribute number, while index *j* denotes the number of measurements (observations):

$$A = \begin{bmatrix} A_{11} & \cdots & A_{i1} \\ \vdots & \ddots & \vdots \\ A_{1j} & \cdots & A_{ij} \end{bmatrix} \tag{6}$$

Matrix ***A'*** of centred values is created by subtracting arithmetic mean of all elements of a given column from each of the column's elements. Correlations between individual attributes (dimensions) are designated in the case when the attributes which describe data are incomparable with each other; alternatively co-variations are designated when the data shares the format and field. Co-variance is calculated according to the following formula:

$$\mathrm{cov}(A_X, A_Y) = \frac{\sum_{j=1}^{n}\left(A_{X,j} - \overline{A_X}\right)\left(A_{Y,j} - \overline{X_Y}\right)}{n-1} \tag{7}$$

and afterward is than arranged into co-variance matrix:

$$\begin{bmatrix} cov(A_1, A_1) & \cdots & cov(A_1, A_i) \\ \vdots & \ddots & \vdots \\ cov(A_i, A_1) & \cdots & cov(A_i, A_i) \end{bmatrix} \tag{8}$$

The main diagonal of the matrix contains co-variance calculations for the same dimensions and it constitutes its variation. Eigenvalues λ, are designated in the co-variance matrix, forming the characteristic (auxiliary) equation of the matrix. Variable λ is subtracted from the main diagonal elements and the matrix determinant is 0. The roots of this equation are called matrix eigenvalues.

$$\begin{vmatrix} a_{11}-\lambda & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22}-\lambda & \ldots & a_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ a_{n1} & a_{n2} & \ldots & a_{nn}-\lambda \end{vmatrix} = 0 \tag{9}$$

Eigenvalues λ are arranged in the order from the greatest to the lowest ($\lambda_1, \lambda_2 \ldots \lambda_n$) and corresponding eigenvectors are designated for each of them ($v_1, v_2 \ldots v_n$). Eigenvectors constitute directions of a new coordinate system, in which the measurement data is presented in such way so as to expose their variability. Projection of measurement data onto a new space is carried out through multiplying the vector with centred measurement data by eigenvectors. The general definition of matrix product states that the product of matrix $A=[a_{ij}]$ of the dimension $n \times r$ multiplied by matrix $B=[b_{jk}]$ of the dimension $r \times m$, is called matrix $C=[c_{ik}]$ of the dimension $n \times m$. Therefore, multiplying one measurement of 8-dimensional centred data by eigenvectors yields the result with the number of dimensions equal to the number of eigenvectors. For instance, a feature vector consisting of two eigenvectors will project raw data onto two-dimensional surface which is easily reflected in a graph. The scheme of such products is presented in Fig. 4.

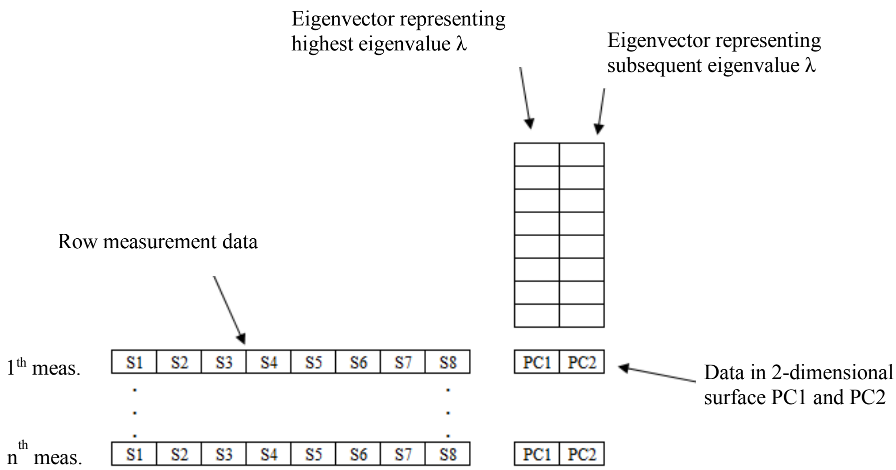

Fig. 4. Graphical scheme depicting the transformation of measurement data into the space of principal components

It is possible to reverse transformation of date, i.e. acquire original measurement data from the space of principal components. A complete and lossless dataset can only be obtained when the data are transformed by means of a feature vector which has as many eigenvectors as the number of dimensions of the measured data. In the case of two or three eigenvectors, it is often possible to obtain over 80% of information concerning the original dataset.

$$OriginalData = (RowFeatureVector^T \times FinalData) + OriginalMean \quad (10)$$

The matrix of eigenvectors, along with the matrix of eigenvalues constitutes a 'key' to transformations between the space of multi-dimensional data and the space of principal components. A given transformation matrix can be implemented in the memory of a micro-controller which controls a multi-sensor meter, thus enabling on-line calculation of principal components during the measurements.

In the case when PCA is employed for static analysis of multi-sensor array response, the number of dimensions is usually equal to the number of utilized sensors.

3.4. Artificial Neural Network

The analysis of data obtained by means of an electronic-nose can also be conducted with Artificial Neural Networks. These networks imitate the structure of a human brain, i.e. a network created by neurons consisting of an axon and numerous dendrites. A neuron gathers signals from other neurons by means of dendrites and subsequently transmits the processed signal to other cells through the axon. The connections between neurons and other cells are called synapses (*Smolarz et al., 2012*). The essence of Artificial Neural Networks is based on a mathematical model describing the principle of data processing, which was graphically represented in Figure A. Following elements were marked: input, weighing, summing, activating. The block weighing input signals x_n corresponds to a biological synaptic connection. The summing element Σ, sums up the weighed signals. If the total sum of the weighed signals exceeds the activation threshold, determined by input Θ, the signal e is transmitted by activation function $f(e)$ (*Osowski, 2000*). This yields the output signal y which corresponds to a signal transmitted through an axon in a brain. The similarities between a neuron and the mathematical model are presented in Tab. 4 in a concise form.

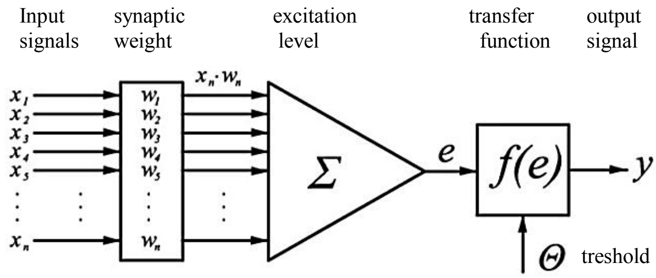

Fig. 5. Graphical scheme depicting a mathematical model of a neuron (Hu and Hwang, 2001)

In order to implement artificial neural networks in the analysis of input data, the learning stage has to be carried out. It involves adjusting the weights in such way so that the input signal equals the expected signal, within the standard deviation. One of the popular learning algorithms used for the analysis of data obtained by multi-sensor systems is back propagation (BP). This algorithm aims to minimize the error constituted by a sum of errors from each neuron of a network, which involves searching for a direction of the highest gradient of the error, and subsequently changing the weight vector in order to make the value of error function decrease towards the greatest descent (Gardner and Dorling, 1998).

Table 4. Similarities between a neural cell and its mathematical model (*Sobczuk et al., 2010*)

Functions and properties	Neural cell	Mathematical model
Type of signal	Electric impulse	Numerical data
Signal input	Dendrite	Data input nodes
Susceptibility to input signal	Capacity of a dendrite to receive a neurotransmitter	Weighing of the input signal
Excitement	Sum of potentials of all cell dendrites	Sum of the weighed signal
Activation	Dependent on the physicochemical properties of a cell	Designated by functions
Signal output	Axon	Data output node

Artificial Neural Networks operating jointly with gas sensor arrays resemble the human olfactory sense to the greatest degree. When the input-output relations are simple, only one layer of hidden neurons is enough (El-Din and Smith, 2002;

Kartam et al., 1997). Otherwise, it is advisable to utilize a greater number of hidden layers. According to R.H. Nielsen (Nielsen, 1987), the number of hidden neurons should be lower than 2n+1, where 'n' corresponds to the number of inputs. If the number of hidden neurons is low, modelling of complex input-output relations becomes impossible. Conversely, networks boasting numerous neurons in the hidden layers are characterized by limited ability of generalization.

4 *Example of measurement system in use*

The presented electronic nose system may find wide application in water, wastewater and sludge management, especially in the assessment of odour nuisance of raw wastewater and, indirectly for evaluation of other parameters level, such as BOD_5, COD, TOC, TSS or nitrogen compounds. The data which will be presented further on was taken from laboratory measurements of wastewater parameters carried out by means of standard analytical methods and by means of and electronic nose, which consisted of eight MOS-type sensors, supplied with air collected above the surface of the analysed wastewater. The surface of wastewater was located inside a laboratory sequencing batch reactor with the activated sludge (Guz et al., 2015; Guz et al., 2016) which operated in a 12-hour cycle.

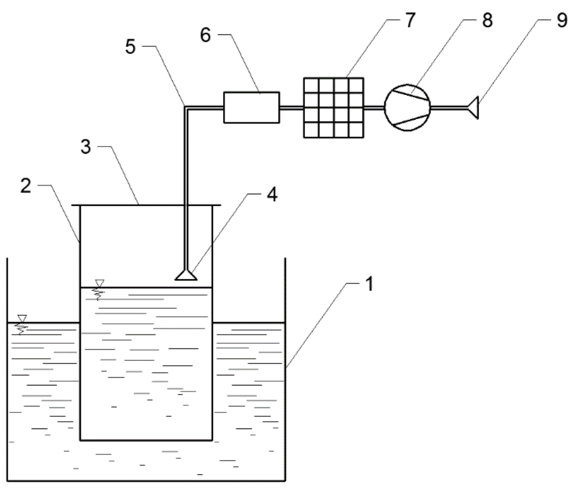

Fig. 6. Diagram of the measurement system: 1) temperature-controlled water bath, 2) $10dm^3$ chamber with the examined wastewater, 3) chamber lid, 4) sampling inlet, 5) teflon pipe, 6) nafion dryer, 7) electronic nose, 8) membrane micro-pump, 9) sampling outlet

The analysis of multi-dimensional data from on-line measurements was conducted with Principal Component Analysis – which is especially helpful in creating initial visualisation of the obtained data – and Artificial Neural Network, used in a detailed data analysis and identifying relationships between the measured parameters. The figure below presents a diagram of a laboratory system used in the measurements.

The utilized electronic nose consists of eight TGS Figaro metal oxide semiconductor gas sensors (Guz et al., 2015). These sensors are characterized with a relatively small size and the maximum power consumption c.a. 300mW. Depending on their sensitivity characteristics, each of them yields a different signal response. Additionally, Honeywell HIH-4000 sensor was utilized for measuring the relative humidity and the gas temperature was measured by means of Dallas DS18B20 digital sensor. The signals from these ten sensors formed an array, which enabled to compensate the temperature and humidity influence on the response.

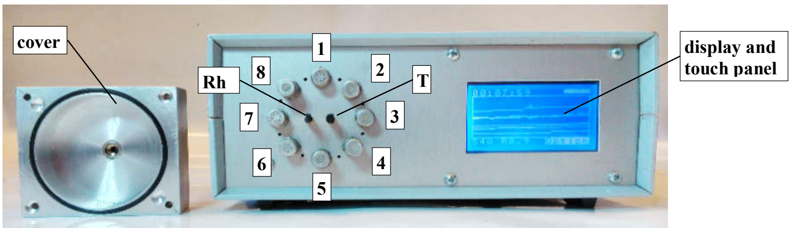

Fig. 7. View of the sensors array with front cover removed: 1 – TGS2600-B00, 2 – TGS2610-C00, 3 – TGS2611-C00, 4 – TGS2612-D00, 5 – TGS2611-E00, 6 – TGS2620-C00, 7 – TGS2602-B00, 8 – TGS2610-D00, T – DS18B20, Rh – HIH-4000

Taking into the account the changing electrical properties of sensors caused by surface chemical reaction occurring between the semiconductor and gas molecules, proportionally to their concentration, the resistive metal oxide semiconductors had to be utilized in gas detection. Sintered tin dioxide (SnO_2), which displays significantly increased conductivity in the reducing gas, constituted the measuring element of the gas sensor. A simple resistive voltage divider can be employed for measuring the resistance of sensors, as recommended by the manufacturers.

The resistive sensor (which is connected to a reference voltage V_C) forms series circuit with a load resistor R_L (connected to the ground) (*www.statsoft.com, 2014*). The sensor resistance is calculated in line with the equation:

$$R_S = R_L\ (V_C - V_{OUT})\ (V_{OUT})^{-1} \tag{11}$$

where R_S denotes resistance of the sensor [Ω], R_L resistance of load resistor [Ω], V_C voltage reference of resistor divider, [V], V_{OUT} output voltage of resistor divider [V]. The 24-bit analog-to-digital converter of the AduC847 micro-controller was used to measure the array response signal.

The adimensional relative resistance was determined in line with *Rs/Ro* ratio, enabling to carry out further calculation of wastewater headspace. *Rs* stands for the average sensor resistance (in kΩ) of readouts from the most stable site at the end of the sample measurements, whereas *Ro* corresponds to the average sensor resistance (in kΩ) of readouts from the most stable site at the end of clean air flushing cycle.

Table 5. Overview of the gas sensors implemented in the e-nose (www.figarosensor.com, 2016)

Sensor type	**Description**
TGS2600-B00 Figaro	general air contaminants, 1–30ppm (H_2)
TGS2602-B00 Figaro	general air contaminants (high sensitivity to VOC and odorous gases), range 1–30ppm of EtOH
TGS2610-C00 Figaro	butane, LP gas, 500–10000
TGS2610-D00 Figaro	butane, LP gas (carbon filter), 500–10000ppm
TGS2611-C00 Figaro	methane, natural gas, 500–10000ppm
TGS2611-E00 Figaro	methane, natural gas (sensor with carbon filter), 500–10000ppm
TGS2612-D00 Figaro	methane, propane, iso-butane, solvent vapors, 1–25% LEL
TGS2620-C00 Figaro	alcohol, solvent vapors, 50–5000ppm

During the Artificial Neural Network learning process which utilized signals form gas sensors array, the initial values of weights were set at random, with the standardized distribution: mean $\overline{w}_{ij} = 0$, variance $s = 1$. An iterative algorithm was employed in order to carry out the learning of Broyden-Fletcher-Goldfarb-Shanno (BFGS) process. The learning, testing, and validation subsets were randomly chosen, corresponding to 70%, 15%, and 15% of the whole dataset, respectively. The latter subset was employed in order to assess the quality of the learned network. The data collected through a parallel experiment conducted in triplicate validated the measuring system.

Evaluation of the network output error (1), involved using the entropy error function or sum of squares (SOS).

$$E_{SOS} = \sum_{i=1}^{N}(y_1 \quad t_i)^2 \tag{12}$$

where N corresponds to the amount of data cases used in learning, y_i represents prediction of network, and t_i is the expected value.

Linear function (identity) x, logistic sigmoid $1/(1+e^{-x})$, hyperbolic tangent $(e^{x} \quad e^{-x})/(e^{x}+e^{-x})$ and exponential e^{-x} and softmax $e^{x}/\sum_i e^{x_i}$, where x – sum of weighted input signals, were employed as an activation function of hidden and output neurons. As a result of a limited range of linear or nonlinear transformation that characterizes the activation function, it is recommended to conduct an appropriate normalization of input data. Without it, the network output would have an extreme value (resulting from the saturation at the asymptotes). Normalization of data was carried out through the linear scaling with 0 as a minimum and 1 as a maximum value (*www.statsoft.com, 2014*).

The measurements were transmitted with the reading frequency of 1 Hz. The steady state responses of gas sensors were recorded. Prior to conducting each measurement of headspace above the wastewater, all sensors were flushed with clean air The average temperature of gases in the sensor chamber amounted to 39.8°C ($\sigma = 2.26$°C), whereas the relative humidity equalled approximately 58,1% ($\sigma = 14,4$%). The temperature in the chamber was elevated as a result of heaters which are built-in the Metal Oxide Semiconductor sensors in order to prevent moisture condensation.

The feedforward artificial neural multi-layer perception (MPL) network was utilized for the analysis of data. The net is composed of ten inputs (eight gas sensors plus single temperature and relative humidity sensors), one hidden layer with n-neurons, as well as one output neuron. The network (Fig.8) was arranged in that particular way in order to achieve minimum complexity and maximum generation ability.

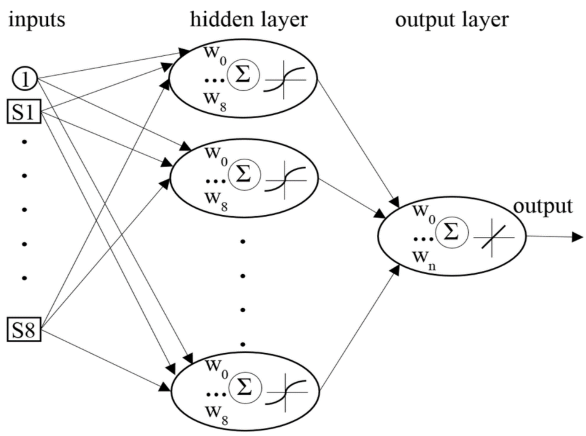

Fig. 8. Neural network architecture (*Guz et al., 2015*)

Figure 9a presents the sensor array output during normal operation and a simulated failure of the sequencing batch reactor. A simulated failure of the reactor begins in the 75th hour, resulting in a decreased sensor resistance Recovery of aerobic conditions following the simulated malfunction was recorded between the 140th and 155th hour. Since about 200th hour it was detected that the process had returned to steady performance represented by regular and cyclic variations on diagram. The chart shows a certain relation, i.e. when the concentration of odorous compounds increases, the all signals of sensors decrease and the network predicts high concentration of odours as a result. Figure 9b presents the predicted odour concentration for the majority of measurements (both normal performance and disturbances) of sequencing batch reactors, determined by means of MLP 10-20-1 network. During failure the average value of odour concentration $\bar{c}_{od}$ reached up to 9.8×10^3 ou_E/m^3, median $Me=5.0\times10^2$ ou_E/m^3 and standard deviation SD 4.8×10^4 ou_E/m^3. During recovery period the values were following: $\bar{c}_{od}$ = $8.3\text{x}10^5$ ou_E/m^3, $Me = 9.2\times10^5$ ou_E/m^3 and $SD = 2.7\times10^5$ ou_E/m^3. For normal reactor performance, the average values of odour concentration were following: $\bar{c}_{od}$ = 1704 ou_E/m^3, Me = 356 ou_E/m^3, SD = 15973 ou_E/m^3. High values of odour concentration were noticed after supplementation of raw sewage to the reactor. High and irregular peaks on the diagram indicate high temporary odour nuisance.

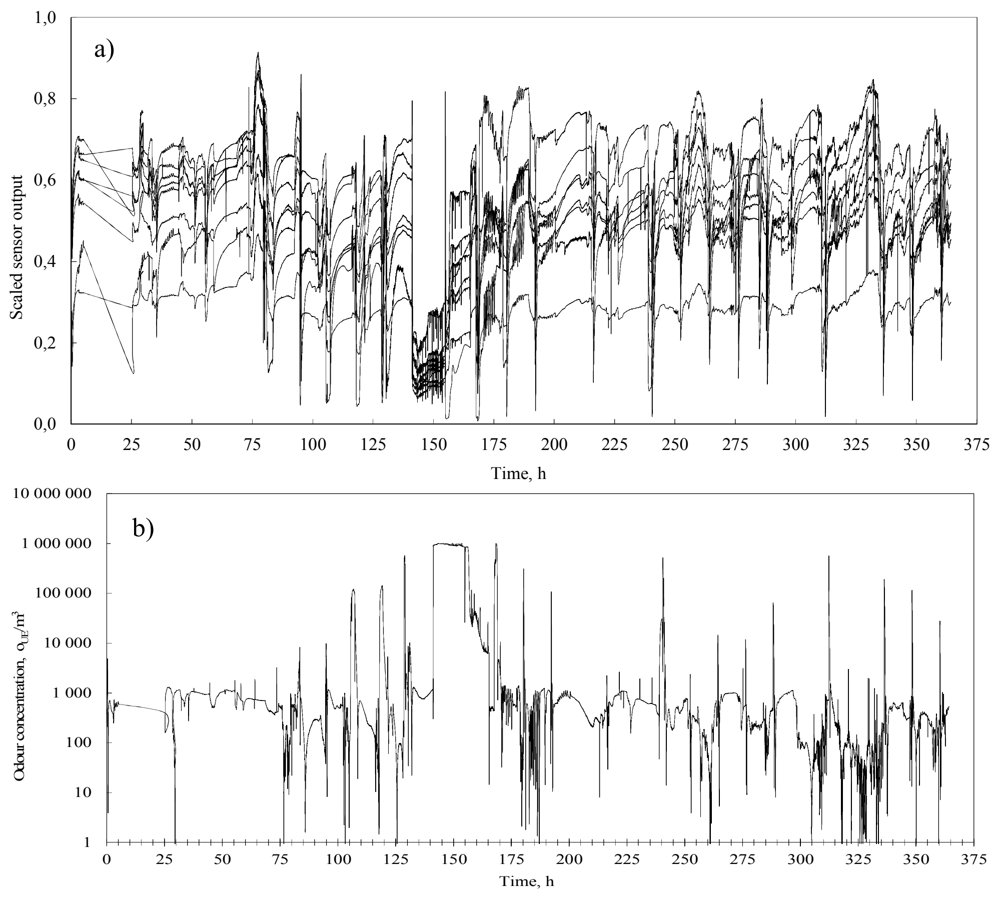

Fig. 9. Sensor array output (a) and predicted odour concentration (b) during normal operation and a simulated failure of the sequencing batch reactor (*Guz et al., 2016*)

5 Summary

The example of electronic nose application presented shows that continuous monitoring of sewage parameters yields information about the parameters of treated wastewater, thus enabling to obtain the data pertaining to the odour nuisance and the processes occurring in the reactor chamber. However, there are still no commercially-available devices which could be used for continuous measurement and control. The estimated data could prove electronic nose to be valuable tool in early warning system within devices of wastewater treatment. It could also bring initial information concerning wastewater parameters and be incorporated into the process of dynamic modelling of wastewater treatment plants.

References

1. Arshak K., Lyons G. M., Cunniffe C., Harris J., Clifford S.: A review of digital data acquisition hardware and software for a portable electronic nose. *Sensor Review*, 23 (4), 332–344, 2003.
2. Bonnin C., Laborie A., Paillard H.: Odor Nuisances Created by Sludge Treatment. In: Stuetz R. Frechen F.B. (Eds.), Odours in Wastewater Treatment: Measurement, Modelling and Control. IWA Publishing, London, 2001.
3. Bourgeois W., Burgess J. E., Stuetz R. M.: On-line monitoring of wastewater quality : a review. *Journal of Chemical Technology and Biotechnology*, 76, 337–348, 2001.
4. Bourgeois W., Gardey G., Servieres M., Stuetz R. M.: A chemical sensor array based system for protecting wastewater treatment plants. *Sensors and Actuators B: Chemical*, 91 (1–3), 109–116, 2003a.
5. Bourgeois W., Hogben P., Pike A., Stuetz R. M.: Development of a sensor array based measurement system for continuous monitoring of water and wastewater. *Sensors and Actuators B: Chemical*, 88 (3), 312–319, 2003b.
6. Bourgeois W., Stuetz R. M.: Use of a chemical sensor array for detecting pollutants in domestic wastewater. *Water Research*, 36 (18), 4505–12, 2002.
7. Brattain W. H., Bardeen J.: Surface Properties of Germanium. *Bell System Technical Journal*, 32 (1), 1–41, 1953.
8. Brennan B.: Odour nuisance. *Water and Waste Treatment*, 36, 30–33, 1993.
9. Brudzewski, K., & Ulaczyk, J. An effective method for analysis of dynamic electronic nose responses. *Sensors and Actuators B: Chemical*, 140 (1), 43–50, 2009.
10. Capelli L., Sironi S., Centola P., Del Rosso R., Grande M. I.: Electronic noses for the continuous monitoring of odours from a wastewater treatment plant at specific receptors: Focus on training methods. *Sensors and Actuators B: Chemical*, 131 (3), 53–62 2008.
11. Craven M. A., Gardner J. W., Bartlett P. N.: Electronic noses — development and future prospects. *Trends in Analytical Chemistry*, 15 (9), 486–493, 1996.

12. Dewettinck T., Van Hege K., Verstraete W.: The electronic nose as a rapid sensor for volatile compounds in treated domestic wastewater. *Water Research*, 35 (10), 2475–2483, 2001.

13. Distante C., Leo M., Siciliano P., Persaud K. C.: On the study of feature extraction methods for an electronic nose. *Sensors and Actuators B: Chemical*, 87 (2), 274–288, 2002.

14. El-Din A. G., Smith D. W.: A neural network model to predict the wastewater inflow incorporating rainfall events. *Water Research*, 36 (5), 1115–1126, 2002.

15. Gardner J. W., Bartlett P. N.: A brief history of electronic noses. *Sensors and Actuators B: Chemical*, 18 (1–3), 210–211, 1994.

16. Gardner M., Dorling S.: Artificial neural networks (the multilayer perceptron)—a review of applications in the atmospheric sciences. *Atmospheric Environment*, 32 (14–15), 2627–2636, 1998.

17. Gostelow P., Parsons S. A., Stuetz R. M.: Review paper: Odour measurements for sewage treatment works. *Pergtamon*, 35 (3), 579–597, 2001.

18. Gutierrez-Osuna R.: Pattern analysis for machine olfaction: a review. *IEEE Sensors Journal*, 2 (3), 189–202, 2002.

19. Guz Ł., Łagód G., Jaromin-Gleń K., Guz E., Sobczuk H.: Assessment of batch bioreactor odour nuisance using an e-nose. *Desalination and Water Treatment*, 57 (3), 1327–1335, 2016.

20. Guz Ł., Łagód G., Jaromin-Gleń K., Suchorab Z., Sobczuk H., Bieganowski A.: Application of gas sensor arrays in assessment of wastewater purification effects. *Sensors*, 15 (1), 1–21, 2015.

21. Haugen J. E., Kvaal K.: Electronic nose and artificial neural network. *Meat Science*, 49(1), 273–286, 1998.

22. Hobbs P. J., Misselbrook T. H., Pain B. F.: Assessment of Odours from Livestock Wastes by a Photoionization Detector, an Electronic Nose, Olfactometry and Gas Chromatography-Mass Spectrometry. *Journal of Agricultural Engineering Research*, 60 (2), 137–144, 1995.

23. Hu Y. H., Hwang J.-N.: Handbook of Neural Network Signal Processing. CRC Press, 2001.

24. James D., Scott S. M., Ali Z., O'Hare W. T.: Chemical Sensors for Electronic Nose Systems. *Microchimica Acta*, 149 (1–2), 1–17, 2004.

25. Kartam N., Flood I., Garrett J. H.: Artificial Neural Networks for Civil Engineers: Fundamentals and Applications. American Society of Civil Engineers New York, 1997.

26. Krzanowski W. J.: Principles of Multivariate Analysis. Oxford University Press, New York 2000.

27. Littarru P.: Environmental odours assessment from waste treatment plants: dynamic olfactometry in combination with sensorial analysers "electronic noses". *Waste Management*, 27 (2), 302–309, 2007.

28. Llobet E., Brezmes J., Vilanova X., Sueiras J. E., Correig X.: Qualitative and quantitative analysis of volatile organic compounds using transient and steady-state responses of a thick-film tin oxide gas sensor array. *Sensors and Actuators B: Chemical*, 41 (1–3), 13–21, 1997.

29. Metcalf L., Eddy H. P.: Wastewater Engineering - Treatment, Disposal, Reuse. McGraw-Hill Inc., New York, 2004.
30. Mielle P., Marquis F.: Gas Sensors Arrays ("Electronic Noses"): A study about the speed r accuracy ratio. *Sensors and Actuators B: Chemical*, 68, 9–16, 2000.
31. Nakamoto T.: Odor Handling and Delivery Systems. In: Pearce T. C., Schiffman S. S., Nagle H. T., Gardner J. W. (Eds.), Handbook of Machine Olfaction Electronic Nose Technology, Viley-Vch., Weinheim, 2006.
32. Nake A., Dubreuil B., Raynaud C., Talou T.: Outdoor in situ monitoring of volatile emissions from wastewater treatment plants with two portable technologies of electronic noses. *Sensors and Actuators B: Chemical*, 106 (1), 36–39, 2005.
33. Nicolas J., Cerisier C., Delva J.: Potential of a Network of Electronic Noses to Assess in Real Time the Odour Annoyance in the Environment of a Compost Facility. *Chemical Engineering Transactions*, 30, 133–138, 2012.
34. Nielsen R. H.: Kolmogorov's Mapping Neural Network Existence Theorem. In: Proceedings of the IEEE First International Conference on Neural Networks, 11–13, 1987.
35. Onkal-Engin G., Demir I., Engin S. N.: Determination of the relationship between sewage odour and BOD by neural networks. *Environmental Modelling & Software*, 20 (7), 843–850, 2005.
36. Osowski S.: Sieci neuronowe do przetwarzania informacji. Oficyna Wydawnicza P.W., Warszawa, 2000.
37. Schaller E., Bosset J. O., Escher F.: "Electronic Noses" and Their Application to Food. *LWT - Food Science and Technology*, 31 (4), 305–316, 1998.
38. Smolarz A., Kotyra A., Wójcik W., Ballester J.: Advanced diagnostics of industrial pulverized coal burner using optical methods and artificial intelligence. *Experimental Thermal and Fluid Science*, 43, 82–89, 2012.
39. Sobczuk H., Guz Ł., Czerwinski J.: Instrumentalne metody w pomiarach zapachowych. In M. Szynkowska, Zwoździak J. (Eds.), Współczesna problematyka odorów. WNT, Wrocław, 2010.
40. Stuetz R., Engin G., Fenner R.: Sewage odour measurements using a sensory panel and an electronic nose. *Water Science and Technology*, 38 (3), 331–335, 1998.
41. Stuetz R. M., Fenner R. A., Engin G.: Assessment of odours from sewage treatment works by an electronic nose, H_2S analysis and olfactometry. *Water Research*, 33 (2), 453–461, 1999a.
42. Stuetz R. M., Fenner R. A., Engin G.: Characterisation of wastewater using an electronic nose. *Water Research*, 33 (2), 442–452, 1999b.
43. Teterycz H.: Grubowarstwowe chemiczne czujniki gazów na bazie dwutlenku cyny, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław, 2005.
44. Wilson A. D., Baietto M.: Applications and advances in electronic-nose technologies. *Sensors*, 9, 5099–5148, 2009.
45. www.figarosensor.com, TGS 2602 - for the detection of Air Contaminants, Figaro USA Inc., 2016.
46. www.statsoft.com, Electronic statistics textbook, Statsoft Inc., 2014.

Influence of chosen parameters on dimensions of suffosion hole after buried water pipe's failure

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Abstract

Water leaking from damaged water supply pipes can cause suffosion effects occurring in soil. Their consequences can be very onerous and threatening the safety of both water supply systems and human's health or even lives. The most extreme examples of suffosion effects are swallow holes, hollows or depressions, especially dangerous in urban areas. One of propositions of minimalizing effects of this kind is the design of protection zones around water supply pipes. Dimensions of protection zones marks the secure distance between water supply pipe and other objects of infrastructure in order to ensure their stability. Depending on suffosion conditions, flowing out water can create holes of different size and form on the soil surface – called suffosion holes. Due to a possible extensive longitudinal shape of suffosion holes, they can strongly influence the size of protection zones.

The purpose of this paper is to present statistically elaborated research's results concerning dimensions of a suffosion holes in dependence on two parameters – leak's area and hydraulic pressure head in a pipe. It is a part of more comprehensive investigations aiming in the determination of a protection zone near water supply pipes. The research was pursued in laboratory setup (scale 1:10) reflecting natural conditions of an operating water supply pipe. Obtained results revealed that pressure head only influences the size of suffosion holes. The dimensions of holes ranged from 1.00 to 9.50 cm (length) and from 0.30 to 6.46 cm (width). As expected, both the length and the width increased with the pressure head rise. The outflow of leakage water did never occur on the soil surface directly above the leaking pipe and it cannot be claimed that water always creates only one suffosion hole (with statistical significance equal to 0.05). The obtained results should be perceive as preliminary and further examinations should be continued, including previous conclusions. Additionally, it is highly recommended to verify the laboratory results by in-situ examinations in real conditions.

Keywords

water supply systems, pipe's failure, exploitation, suffusion

1 Introduction

Breakages and damages of water network pipes causing leakages are common problems for corporations managing distribution systems all over the world. The intensity of water outflowing from a damaged pipe is various – from undetectable small leakages to outflow of high flow-rates requiring immediate attention (*Buchberger and Nadimpalli, 2004; Eliades and Polycarpou, 2012; Lambert and Morrison, 1996*). Moreover, leakages are inevitable and difficult to predict (*Hotloś, 2009; Romano and Kapelan, 2013*). They cause financial costs directly and indirectly as well as social and environmental losses (*Covas and Ramos, 2010; Hotloś, 2006; Siwoń et al., 2004; Xu et al., 2011*). Water leaking from buried supply pipes can generate the transport of fine soil particles causing suffosion effects. Consequences of suffosion can be very onerous and threatening the safety of both water supply systems and human's health or even lives. The most extreme examples of suffosion effects are swallow holes, hollows or depressions, especially dangerous in urban areas (*Khomenko, 2009*). In Poland, occurrence of internally unstable soils, especially in mountain areas and the loess uplands (*Bernatek, 2014*), as well as a high failure intensity rate of water supply systems, compared to other countries (*Kowalski and Miszta-Kruk, 2013; Kutyłowska and Hotloś, 2014, Kwietniewski, 2011*), are factors increasing the risk of the emergence of this kind of problems.

One of the propositions of minimalizing the suffosion effect's onerousness is the design of protection zones around buried water supply pipes (*Kowalski and Jaromin, 2011; Iwanek et al., 2014*). It is assumed that an outflow of water on the soil surface after a possible failure of a water pipe will occur inside the zone. Thus, dimensions of protection zones marks the secure distance between water supply pipe and infrastructure objects, e.g. buildings, in order to ensure the construction's stability. Decisions about infrastructure and settlement inside the zone should be taken by corporations managing water distribution systems so as to limit social, economical and environmental costs in the case of a water network failure. Depending on suffosion conditions, flowing out water can create holes of different size and form on the soil surface – called suffosion holes. Due to a possible extensive longitudinal shape of suffosion holes, they can strongly influence the size of protection zones.

The purpose of this paper is to present statistically elaborated research's results concerning dimensions of a suffosion holes in dependence on two parameters – leak's area and hydraulic pressure head in a pipe. It is a part of more comprehensive investigations aiming in the determination of a protection zone near water supply pipes.

2 Materials and Methods

An outflow of water on the soil surface after a failure of a water pipe was investigated during laboratory simulation. Tests required construction of the setup (Fig.1) reflecting natural operation conditions scaled 1:10, consisting of an intentionally damaged water pipe (2) buried in medium sand filling a box (1). The pipe was supplied by water from a container (4) located on the assumed height.

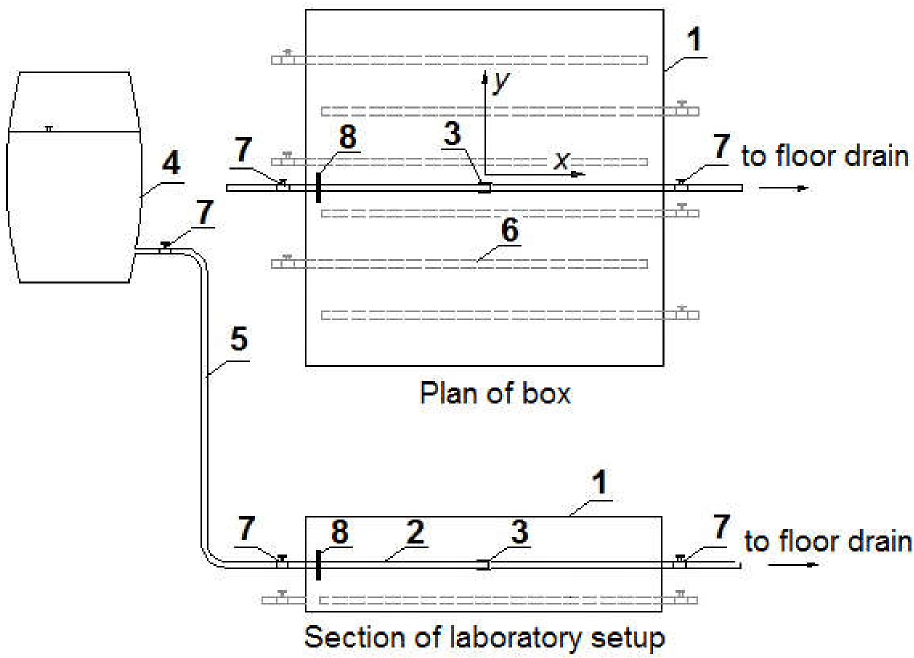

Fig. 1. Scheme of the laboratory setup for physical simulation of water supply failure (*Iwanek et al., 2014*; *Iwanek et al., 2016*):
1 – sand-filled box, 2 – water pipe, 3 – bell-and-spigot connection (place of leakage), 4 – container, 5 – hose, 6 – drainage system, 7 – valves, 8 – holder

Tests were conducted for 4 different leak areas – 4.71 cm^2, 5.58 cm^2, 9.42 cm^2 and 12.25 cm^2. Internal water pressure head in the pipe varied from 3.25 to 6.0 m H_2O depending on the height of the container (4) and the water level in it. Details about the laboratory setup, parameters of sand filling the box and realization of the experiment are given in the article of *Iwanek et al*. (2016).

The next part of the investigations was the statistical analysis of test results of measuring the average dimensions of suffosion holes created on the sand surface by water outflowing from a damaged buried pipe during laboratory tests (Fig.2). Both values of a length (*a*) and a width (*b*) of a suffosion hole were treated as a single variable, obtained in each variant of a leak area and pressure head as an arithmetical mean of values measured in repetitions of a test in the same conditions. The first part of the statistical analysis was to determine an influence of a leak area and a hydraulic pressure head in the pipe on dimensions of a suffosion hole. The influence was evaluated on the basis of linear, exponential, logarithmic, polynomial and power regression models.

Next, the number of suffosion holes creating on the soil surface was determined. To this aim, the null hypothesis that an expected number of holes creating during each experiment equals 1 ($H_0: \mu_0 = 1$), contrasted with an alternative hypothesis $H_1: \mu_0 > 1$ was verified with the significance level $\alpha = 0.05$ on the basis of statistical test U according to the formula (1):

$$U = \frac{\overline{X} - \mu_0}{\sigma} \sqrt{n} \tag{1}$$

where: $\overline{X}$ – arithmetical mean of holes numbers in n experiments [-], μ_0 – expected number of the holes ($\mu_0 = 1$), σ – standard deviation, n – number of all experiments [-].

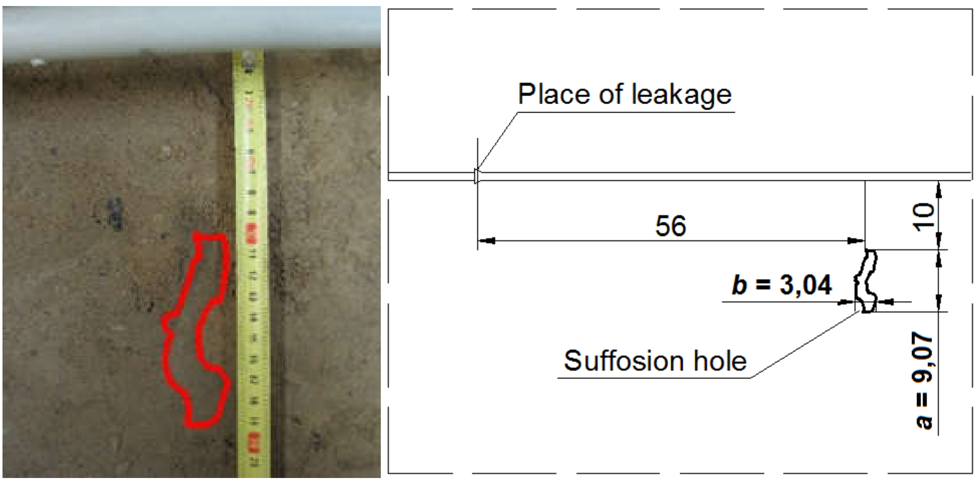

Fig. 2. Suffosion hole created on the sand surface by water outflowing from a damaged pipe – leak area $A = 4.71$ cm^2, pressure head $H = 4.5$ m H_2O, 2nd repetition of the experiment

3 Results and Discussion

Taking into account results of all repetitions of laboratory experiments, the minimal value of the holes length on soil surface equalled 0.50 cm, whereas the maximum – 10.17 cm. The mean value of the holes length on soil surface ranged from 1.00 to 9.50 cm depending on pressure head in the water pipe and leak area (Fig. 3). The results of analysis of pressure head influence on the suffosion holes length are presented in Fig. 4–7 and Tab.1–4.

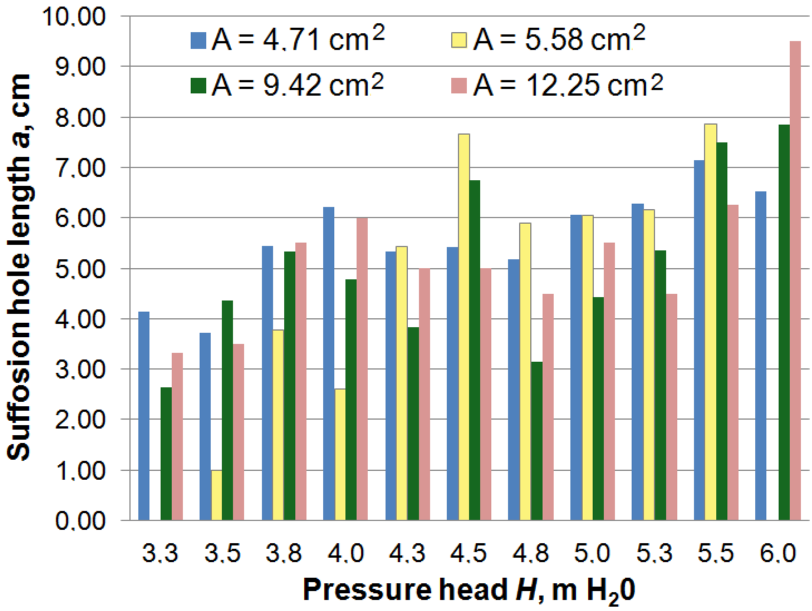

Fig. 3. Arithmetic mean value of suffosion holes length for different leak areas *A* and pressure head *H* in a water pipe

For all cases in question, the tendency of the length of suffosion holes to increase with rising pressure head in a pipe was observed. However, the satisfactory fitting regression lines to observed data (with coefficient of determination $R^2 > 0.6$) occurred for leak areas of 4.71 cm^2 and 5.58 cm^2 (Tab. 1–2) only. For $A = 9.42$ cm^2, the fitting was unsatisfactory ($R^2 < 0.5$) (Tab. 3) and for $A = 12.25$ cm^2, a coefficient of determination was higher than 0.5 just for a polynomial model (Tab. 4). For all but one considered areas, a polynomial regression model described the best fitting. For $A = 4.71$ cm^2, a power model gave the best fitting result. Analyzing a shape of regression lines and coefficients in regression equations, it can be noticed, that individual kinds of regression models for $A = 9.42$ cm^2 and for $A = 12.25$ cm^2 are very close to each other.

Table 1. Characteristics of regression models for data *a* in the case of $A = 4.71$ cm^2

Regression model	No of model in Fig. 4	Regression equation	R^2
Exponential	1	$y = 4.1340e^{0.0476x}$	0.6557
Linear	2	$y = 0.2514x + 4.0818$	0.6754
Logarithmic	3	$y = 1.1257\ln(x) + 3.7989$	0.6837
Polynomial	4	$y = -0.0107x^2 + 0.3793x + 3.8045$	0.6849
Power	5	$y = 3.8887x^{0.2178}$	0.6940

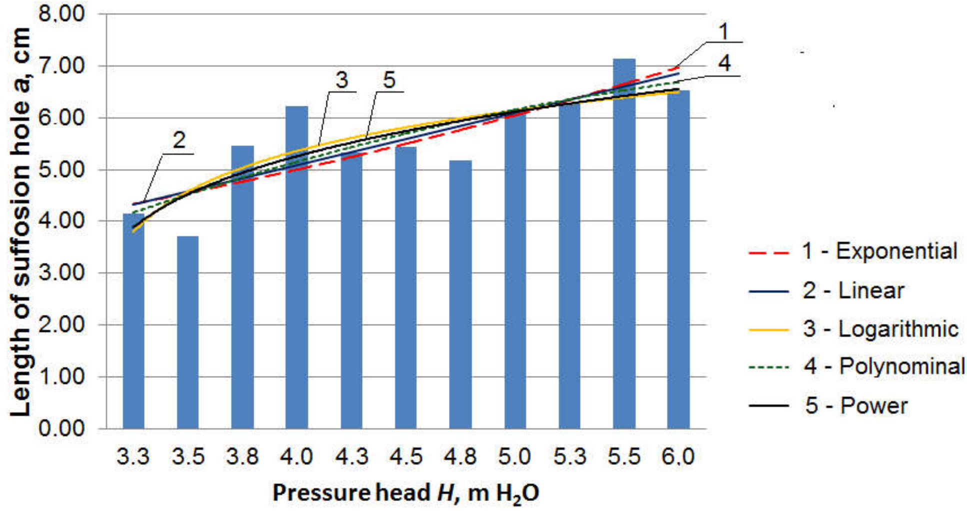

Fig. 4. Regression lines characterizing dependence between the suffosion holes length and pressure head *H* in a water pipe for the case of A = 4.71 cm^2

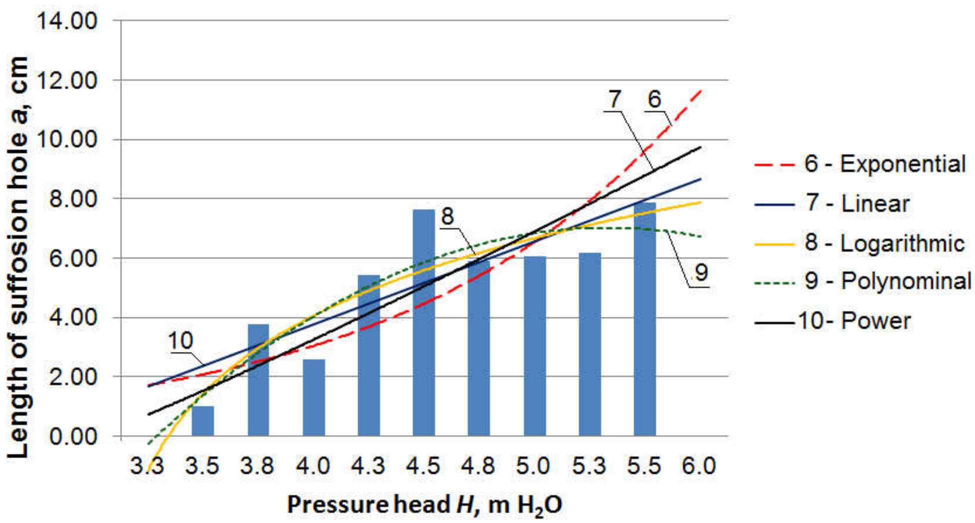

Fig. 5. Regression lines characterizing dependence between the suffosion holes length and pressure head *H* in a water pipe for the case of A = 5.58 cm^2

Table 2. Characteristics of regression models for data *a* in the case of A = 5.58 cm^2

Regression model	No of model in Fig. 5	Regression equation	R^2
Exponential	6	$y = 1.4141e^{0.1916x}$	0.6326
Linear	7	$y = 0.7002x + 0.9579$	0.7051
Logarithmic	8	$y = 3.7724\ln(x) – 1.1722$	0.7850
Polynomial	9	$y = – 0.1051x^2 + 1.9619x – 2.1262$	0.7868
Power	10	$y = 0.7236x^{1.0843}$	0.7768

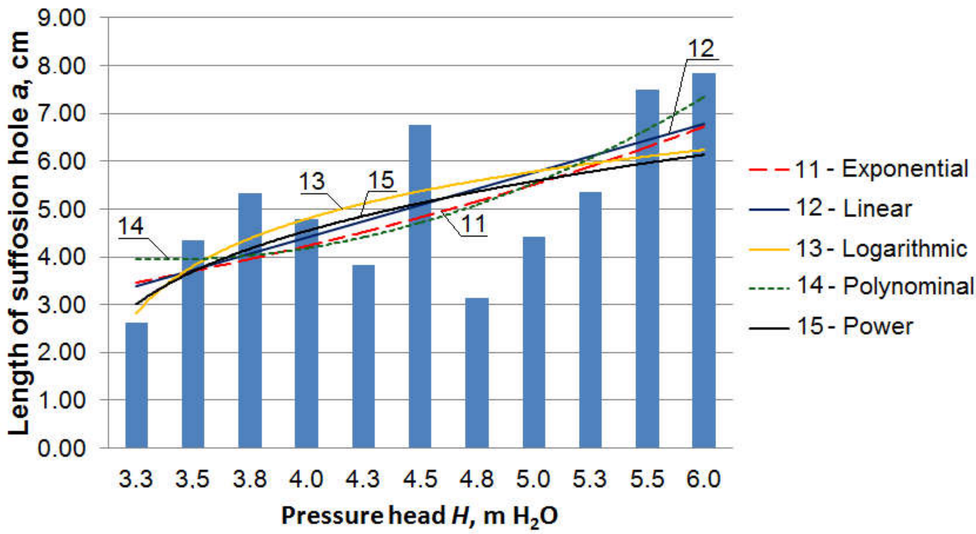

Fig. 6. Regression lines characterizing dependence between the suffosion holes length and pressure head H in a water pipe for the case of A = 9.42 cm^2

Table 3. Characteristics of regression models for the case of A = 9.42 cm^2

Regression model	No of model in Fig. 6	Regression equation	R^2
Exponential	11	$y = 3.2408e^{0.0664x}$	0.4091
Linear	12	$y = 0.3396x + 3.0495$	0.4409
Logarithmic	13	$y = 1.4266\ln(x) + 2.8174$	0.3926
Polynomial	14	$y = 0.0373x^2 – 0.1076x + 4.0185$	0.4823
Power	15	$y = 3.0083x^{0.2972}$	0.4135

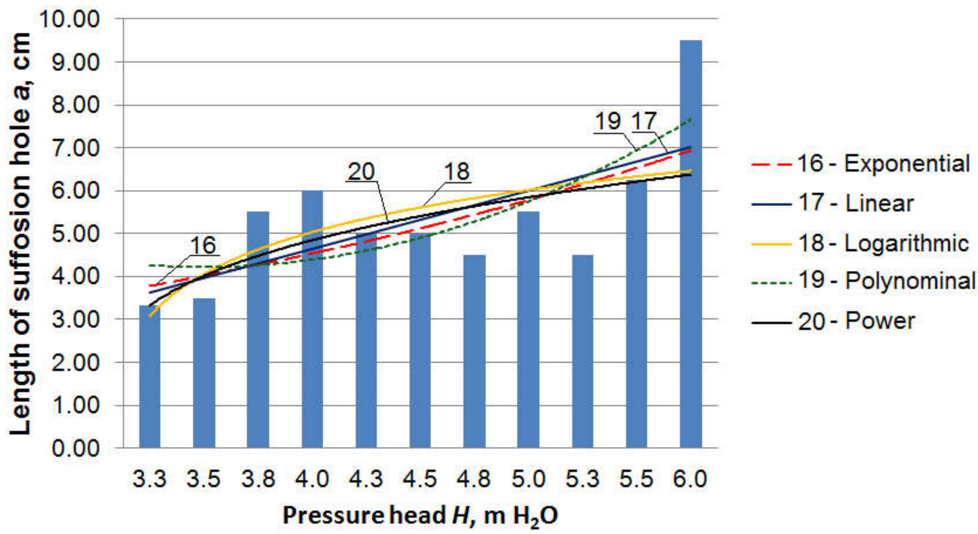

Fig. 7. Regression lines characterizing dependence between the suffosion holes length and pressure head *H* in a water pipe for the case of A = 12.25 cm^2

Table 4. Characteristics of regression models for data *a* in the case of *A* = 12.25 cm^2

Regression model	No of model in Fig. 7	Regression equation	R^2
Exponential	16	$y = 3.5577e^{0.0607x}$	0.4937
Linear	17	$y = 0.3395x + 3.2882$	0.4581
Logarithmic	18	$y = 1.4115\ln(x) + 3.0796$	0.3995
Polynomial	19	$y = 0.0425x^2 – 0.1702x + 4.3927$	0.5140
Power	20	$y = 3.3275x^{0.271}$	0.4964

Similarly to the length, the width of suffusion holes on soil surface was analyzed. In all repetitions of the laboratory experiments, values of the holes width ranged from 0.30 cm to 6.46 cm, whereas the mean values in the same conditions of pressure head in a water pipe and leak area ranged from 0.75 to 5.50 cm (Fig. 8). The results of analysis of pressure head influence on the suffosion holes width are presented in Fig. 9–12 and Tab.5–8.

The width of suffosion holes tended to increase with increasing pressure head in a pipe for all analysed leak areas. The satisfactory fitting regression lines to the observed data ($R^2 > 0.6$) was observed for all regression models for leak area of 4.71 cm^2 and for linear and polynomial model for *A* = 9.42 cm^2 (Tab. 5 and 7). For the cases of *A* = 5.58 cm^2 and *A* = 12.25 cm^2, the fitting was very poor ($R^2 \leq 0.3$) (Tab. 6 and 8). The best fitting to the observed data was described by a power regression model for $A = 5.58$ cm^2 and by a polynomial model for the rest leak areas.

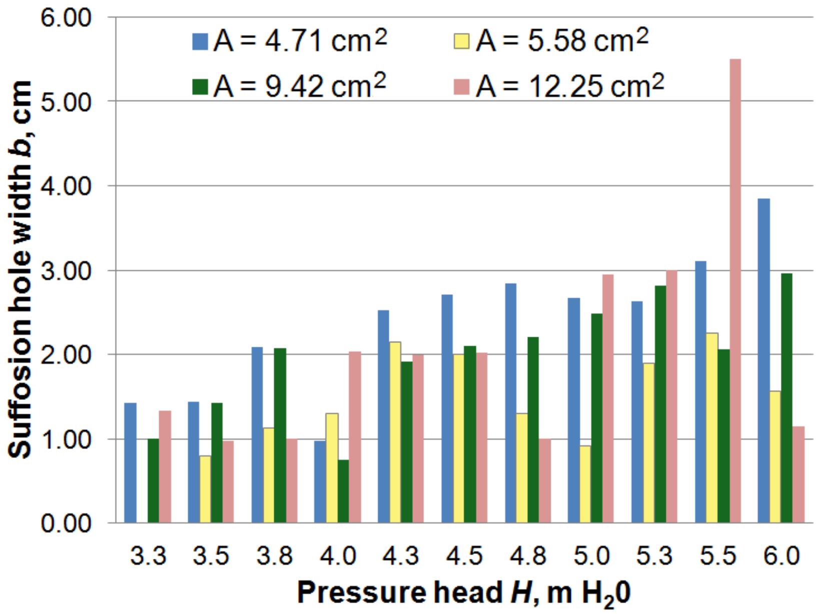

Fig. 8. Arithmetic mean value of the suffosion holes width for different leak areas *A* and pressure head *H* in a water pipe

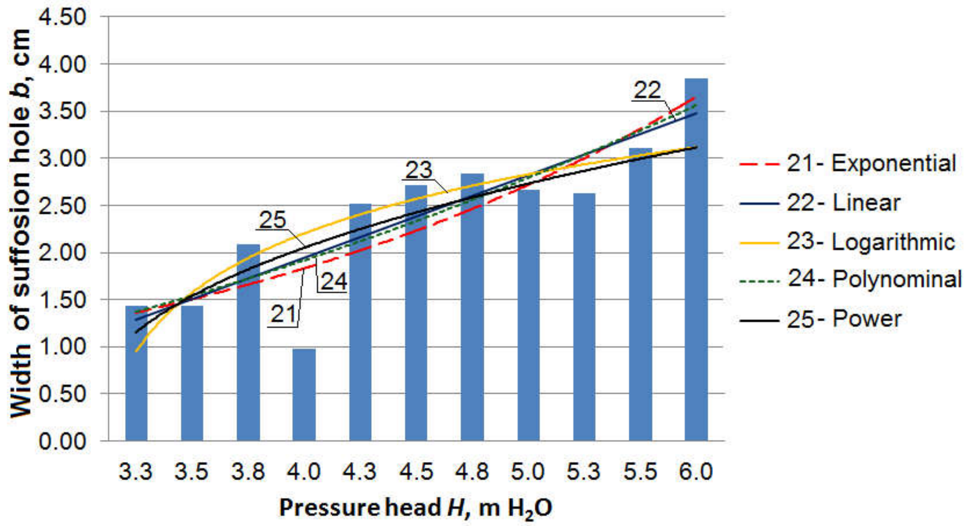

Fig. 9. Regression lines characterizing dependence between the suffosion holes width and pressure head *H* in a water pipe for the case of A = 4.71 cm^2

Table 5. Characteristics of regression models for data *b* in the case of $A = 4.71$ cm^2

Regression model	No of model in Fig. 9	Regression equation	R^2
Exponential	21	$y = 1.2358e^{0.0986x}$	0.6485
Linear	22	$y = 0.2191x + 1.0736$	0.7532
Logarithmic	23	$y = 0.9034\ln(x) + 0.9507$	0.6464
Polynomial	24	$y = 0.0053x^2 + 0.1556x + 1.2112$	0.7567
Power	25	$y = 1.1576x^{0.4129}$	0.5740

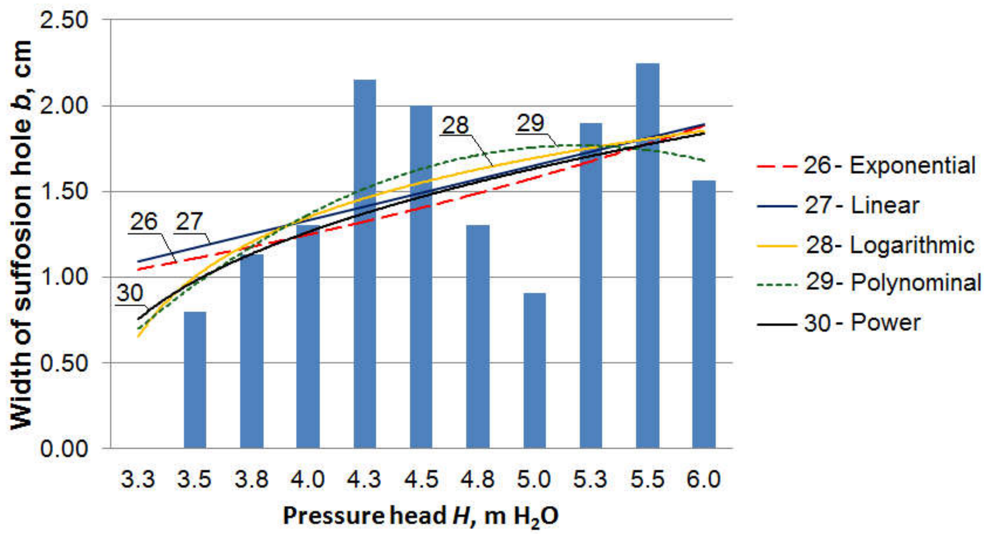

Fig. 10. Regression lines characterizing dependence between the suffosion holes width and pressure head *H* in a water pipe for the case of A = 5.58 cm^2

Table 6. Characteristics of regression models for data *b* in the case of $A = 5.58$ cm^2

Regression model	No of model in Fig. 10	Regression equation	R^2
Exponential	26	$y = 0.9858e^{0.0589x}$	0.2412
Linear	27	$y = 0.0804x + 1.0076$	0.2180
Logarithmic	28	$y = 0.4993\ln(x) + 0.6561$	0.2822
Polynomial	29	$y = 0.0053x^2 + 0.1556x + 1.2112$	0.2853
Power	30	$y = 0.756x^{0.3704}$	0.3199

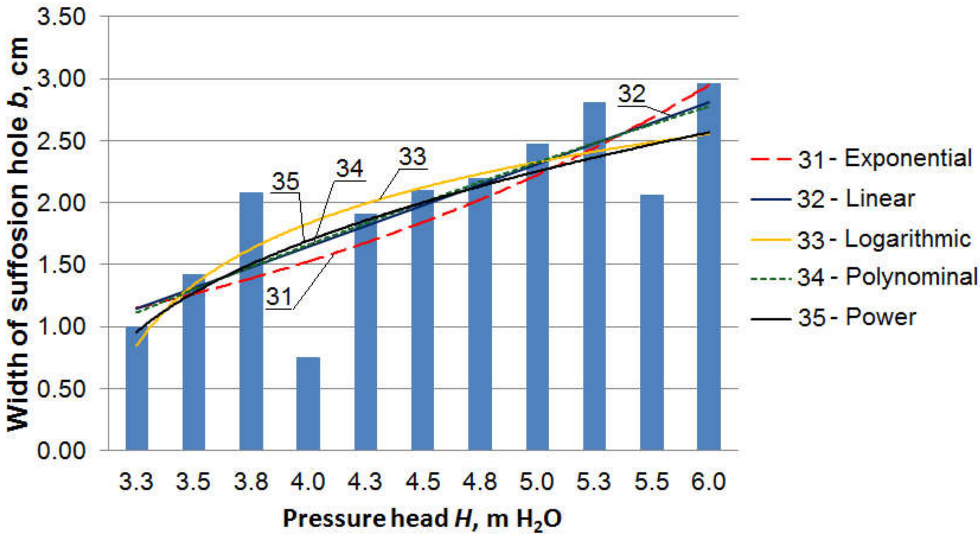

Fig. 11. Regression lines characterizing dependence between the suffosion holes width and pressure head *H* in a water pipe for the case of A = 9.42 cm^2

Table 7. Characteristics of regression models for data *b* in the case of *A* = 9.42 cm^2

Regression model	No of model in Fig. 11	Regression equation	R^2
Exponential	31	$y = 1.0477e^{0.0941x}$	0.5358
Linear	32	$y = 0.1664x + 0.9809$	0.6382
Logarithmic	33	$y = 0.7134\ln(x) + 0.8441$	0.5923
Polynomial	34	$y = -0.0023x^2 + 0.1941x + 0.9209$	0.6392
Power	35	$y = 0.9577x^{0.4113}$	0.5167

Table 8. Characteristics of regression models for data *b* in the case of *A* = 12.25 cm^2

Regression model	No of model in Fig. 12	Regression equation	R^2
Exponential	36	$y = 1.0638e^{0.0866x}$	0.2622
Linear	37	$y = 0.2184x + 0.7771$	0.2869
Logarithmic	38	$y = 0.8991\ln(x) + 0.6566$	0.2455
Polynomial	39	$y = -0.0058x^2 + 0.2883x + 0.6256$	0.2885
Power	40	$y = 0.9817x^{0.377}$	0.2509

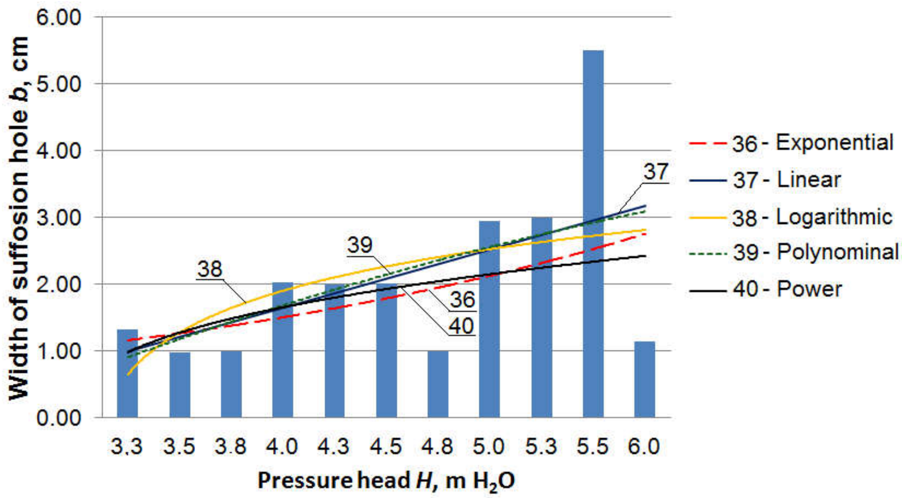

Fig. 12. Regression lines characterizing dependence between the suffosion holes width and pressure head H in a water pipe for the case of A = 12.25 cm^2

As far as the leak area influence on dimensions of a suffosion hole is considered, no tendency was observed, neither for the length, nor for the width (Fig. 3 and 8). However, it should be emphasized, that four different values of leak area are too less to analyze regression or to create general conclusions.

Table 9. Mean numbers N of suffosion holes for different leak areas A (cm^2) and pressure head H (m H_2O) in a water pipe

A (cm^2) \ H (m H_2O)	3.25	3.5	3.8	4.0	4.3	4.5	4.8	5.0	5.3	5.5	6.0
4.71	1.00	1.00	1.00	1.00	1.00	1.50	1.50	1.50	1.50	1.00	1.50
5.58	-	1.00	1.50	1.00	1.00	1.00	1.00	1.00	1.50	1.30	1.50
9.42	1.00	1.50	1.00	1.00	1.00	1.00	1.00	1.50	2.00	1.50	1.50
12.25	1.00	1.00	1.00	2.00	1.00	1.00	1.00	1.50	1.00	2.00	1.00

The last part of the analysis was determination of an expected number of suffosion holes. In 91 repetitions of the laboratory experiment, a single hole occurred 73 times, two holes – 17 times and three holes – once. Arithmetical mean values of holes numbers in the same conditions of laboratory tests are presented in Tab. 9. Because the tests results were dominated by single holes, a null hypothesis was $H_0: \mu_0 = 1$ and an alternative hypothesis H_1: $\mu_0 > 1$. The obtained results indicated that the null hypothesis should be rejected in favor of the alternative one. Moreover, clearly lower number of washed out holes was observed when pressure head in a water pipe $H < 5$ m H_2O than for $H \geq 5$ m H_2O.

4 Summary and Conclusions

Results of physical simulation of buried water pipe breakage, conducted in laboratory conditions, indicated that pressure head influences the size of suffosion holes. As expected, both the length and the width increased with the pressure head rise with similar tendency. The best fitting regression lines to observed data occurred for polynomial model for 6 cases and power model for 2 cases. The highest values of a coefficient of determination R^2 were obtained for the hole length a in the case of $A = 5.58$ cm^2. Analyzing the leak area influence on suffosion hole size, no tendency was observed, mainly because of the insufficient number of different leak areas.

The outflow of leakage water did never occur on the soil surface directly above the leaking pipe and it cannot be claimed that water always creates only one suffosion hole (with statistical significance equal to 0.05). The number of suffosion holes was higher than 1 more frequently for pressure head in a pipe $H < 5$ m H_2O than for $H \geq 5$ m H_2O.

Results of the analysis should be treated as preliminary and investigations of water network pipe failures should be continued, including previous conclusions. Moreover, it is highly recommended to verify the laboratory results by in-situ tests in real conditions.

Acknowledgments

The article has been financed through statutory activities of Department of Water Supply and Wastewater Disposal of Environmental Engineering Faculty of Lublin University of Technology.

References

1. Buchberger S. G., Nadimpalli G.: Leak estimation in water distribution systems by statistical analysis of ow readings. *Journal of Water Resources Planning and Management – ASCE*, 130 (4), 321–329, 2004.

2. Bernatek A.: Rola sufozji w rozwoju rzeźby – stan i perspektywy badań. *Przegląd Geograficzny*, 86, 53–76, 2014.

3. Covas D., Ramos H.: Case studies of leak detection and location in water pipe systems by inverse transient analysis. *Journal of Water Resources Planning and Management*, 136 (2), 248–257, 2010.

4. Eliades D.G., Polycarpou, M.M.: Leakage fault detection in district metered areas of water distribution systems. *Journal of Hydroinformatics*, 14.4, 992–1005, 2012.

5. Hotloś H.: Analiza uszkodzeń i kosztów naprawy przewodów wodociągowych w okresie zimowym. *Ochrona Środowiska*, 31 (2), 41–48, 2009 (in Polish, with English abstract).

6. Hotloś H.: Metodyka i przykłady prognozowania kosztów naprawy przewodów wodociągowych. *Ochrona Środowiska*, 28, 49–542006, (in Polish, with English abstract).

7. Iwanek M., Kowalska B., Hawryluk E., Kondraciuk K.: Distance and time of water effluence on soil surface after failure of buried water pipe. Laboratory investigations and statistical analysis. *Eksploatacja i niezawodnosc – Maintenance and Reliability*, 18 (2), 278–284, 2016, http://dx.doi.org/10.17531/ein.2016.2.16.

8. Iwanek M., Kowalski D., Kowalska B., Hawryluk E., Kondraciuk K.: Experimental investigations of zones of leakage from damaged water network pipes. In: C. A. Brebbia, S. Mambretti (eds.): *Urban Water II. WIT Transactions on the Built Environment*, 139, 257–268, Southampton, Boston, UK: WIT Press 2014, http://dx.doi.org/10.2495/uw140221.

9. Khomenko, V. P.: Suffosion hazard: today's and tomorrow's problem for cities (Paper 577). In: Culshaw M.G., Reeves H.J., Jefferson I., Spink T.W. (eds.): *Engineering Geology Special Publication*, No 22, Geological Society: London 2009 (on CD-ROM insert).

10. Kowalski D., Jaromin K.: Metoda wyznaczania zasięgu strefy ochrony wodociągowych przewodów tranzytowych. *Proceedings of ECOpole*, 4, 419–424, 2011.

11. Kowalski D., Miszta-Kruk K.: Failure of water supply networks in selected Polish towns based on the eld reliability tests. *Engineering Failure Analysis*, 35, 736–742, 2013.

12. Kutyłowska M., Hotloś H.: Failure analysis of water supply system in the Polish city of Głogów. *Engineering Failure Analysis*, 41, 23–29, 2014.

13. Kwietniewski M. Awaryjność infrastruktury wodociągowej i kanalizacyjnej w Polsce w świetle badań eksploatacyjnych. *XXV Konferencja Naukowo-Techniczna Awarie Budowlane*, 127–140, 2011.

14. Lambert A., Morrison J. A. E.: Recent developments in application of 'bursts and background estimates' concepts for leakage management. *Water and Environment Journal*, 10, 100–104, 1996.

15. Romano M., Kapelan Z.: Geostatistical techniques for approximate location of pipe burst events in water distribution systems. *Journal of Hydroinformatics*, 15 (3), 634–635, 2013.

16. Siwoń Z., Cieżak W., Cieżak J.: Praktyczne aspekty badań strat wody w sieciach wodociągowych. *Ochrona Środowiska*, 26 (4), 25–30, 2004.

17. Xu Q., Chen Q., Li W.: Application of genetic programming to modeling pipe failures in water distribution systems. *Journal of Hydroinformatics*, 13 (3), 419–428, 2011.

Adsorption of biologically active substances on carbonaceous adsorbents – effect of operational parameters on removal degree and kinetics

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Abstract

This study determined the removal degree of four different compounds classified as biologically active compounds i.e. benzo(a)pyrene (BaP), anthracene (ANT), diclofenac (DCL), pentachlorophenol (PCP), octylphenol (OP) in adsorption by the activated carbon and comparatively by the carbon nanotubes. The sorption process was carried out in the batch system for deionized water solution of 500 µg/L under the competitive and uncompetitive adsorption conditions. Effect of different operational parameters such as adsorbent dose, initial concentration, temperature, pH on the removal degree of micropollutants and kinetics of adsorption was investigated. It was found that the removal efficiency was in the range from 5% to 98%. The highest removal degree was observed for benzo(a)pyrene and anthracene, while the lowest removal degree was obtained for diclofenac. Moreover, removal of these PAHs increased with the increasing temperature from 5°C to 35°C. In terms of adsorption of the selected biologically active compounds, sorption potential of carbon nanotubes and activated carbon was comparable, however adsorption on carbon nanotubes proceeded a dozen times faster. It was found also, that removal degree of benzo(a)pyrene was higher under the competitive adsorption conditions than under the uncompetitive.

Keywords

Biologically active substances, adsorption, activated carbon, carbon nanotubes

1 Introduction

In the recent years, increasing attention has been focused on the presence of micropollutants in the aquatic environment. They can significantly degrade the quality of water bodies and pose a serious threat to aquatic ecosystems (*Jiang et al., 2005; Lee et al., 2002; Gibson et al., 2007, Nakada et al., 2006*). The group of anthropogenic micropollutants, that are adverse for the biological equilibrium in the aquatic environment and human health include: phenols, non-biodegradable organochlorine compounds, pesticides, polycyclic aromatic hydrocarbons (PAHs), detergents, heavy metals. Pharmaceuticals and personal care products (PPCPs) as well as endocrine disrupting compounds (EDCs) require particular concern due to their biological activity and potential role as an estrogen receptor agonist for human mammals (*Fernandez et al., 2005; Ge et al., 2010*). Due to their adverse behavior, some micropollutants including alkylophenol, EDCs, pharmaceuticals have been termed as “priority hazardous substances” in the Water Frame European Directives (2000/60/EC). These standards establish the acceptable, medium, annual concentration of the substances in all surface water bodies.

Numerous advanced techniques have been developed for the elimination of emerging micropollutants from water and sewage streams, including the advanced oxidations process (*Bohdziewicz et al., 2014; Martínez-Zapata et al., 2013; Vela et al., 2012*), membrane techniques (*Dudziak, 2012; Dudziak and Bodzek, 2009; Musbah et al., 2013; Kamińska et al., 2015),* sorption on carbonaceous adsorbents and biological decomposition (*Bohdziewicz and Kamińska, 2013a, b; El-Naas et al., 2010; Upadhyayula et al., 2009; Long and Yang, 2001)*. The adsorption process seems to be considered as one of the cheapest and simplest method to remove micropollutants from wastewater and drinking water. Adsorption potential of conventional sorbents such as the powdered activated carbon (PAC) and granulated activated carbon (GAC) has been frequently used to remove phenols, pesticides heavy metals, polycyclic aromatic hydrocarbons from wastewater *(Bohdziewicz and Kamińska, 2013a; El-Naas et al., 2010)*. On the other hand, various types of nanomaterials have been recently implemented. They present the promising potential in adsorption of micropollutants (*Upadhyayula et al., 2009*). Among nanomaterials which could be used as sorbents are highlighted carbon nanomaterials such as fullerene and carbon nanotubes. In comparison to the conventional sorbents, nanomaterials show numerous advantages such as larger surface area, controlled pore size, well developed mesopores, all properties cause unique adsorption capacity *(Bohdziewicz and Kamińska, 2013a; Patiño et al., 2015). Long and Yang (2001)* first reported that carbon nanotubes (CNTs) showed higher adsorption efficiency for dioxin than activated carbon.

In terms of adsorption, most of the studies describe kinetics and equilibrium of sorption micropollutants, however the real removal efficiency was rarely discussed. The main objectives of this study were: (1) to investigate the effect of crucial operational parameters of adsorption on their removal degree i.e. initial concentration of chemicals, adsorbent dose, pH, temperature (2) to compare the removal degree of micropollutants under the competitive and uncompetitive adsorption conditions (3) to determine kinetics of adsorption of the selected biologically active compounds on activated carbon and carbon nanotubes.

2 *Materials and Methods*

2.1. Chemicals

All substances (pentachlorophenol, diclofenac, anthracene, benzo(a)pyrene) were purchased from Sigma Aldrich (Poland). Their properties are shown in table 1. The stock solutions of compounds were prepared with methanol (analytical standard), Avantor (Poland). Then the working solutions (100 and 500 µg/L) of compounds were obtained by diluting the stock solution with pure water. Pure water was taken directly from Milli-Q water purification system (Millipore LLC, Poland). NaOH and HCl were purchased from POCH, Inc. (Poland).

Table 1. Properties of compounds

Compound	Molecular weight [g/mol]	$\log K_{ow}$ [a]	$\log K_{ow}$ [b]
Pentachlorphenol (PCP)	266.34	4.40	5.12
Diclofenac (DCL)	296.15	4.51	4.51
Benzo(a)pyrene (BaP)	252.31	6.35	6.13
Anthracene (ANT)	178.22	4.45	4.45

[a] $\log K_{ow}$ values as calculated from "SRC *Kow* WIN"

[b] data from https://pubchem.ncbi.nlm.nih.gov

2.2. Adsorption experiments

Powder activated carbon and single walled carbon nanotubes (SWCNT) were used in the presented experiment. Activated carbon, named SX2 with BET surface area at the level of 821.76 m^2/g was obtained from Avantor (Poland). SWCNT (BET: 467.38 m^2/g) were purchased from Chengdu Organic Chemistry Ltd., Chinese Academy of Science.

Adsorption experiments were conducted in 50 ml glass flasks equipped with a ground-in stopper using a batch system for 2 hours. In this study, the initial concentration of compounds was at the level of 500 μg/L, apart from the series, oriented on the effect of initial concentration on the removal degree. In the all applied experimental series, the flasks were shaken at 200 rpm/min until reaching the state of equilibrium. Then the nanotubes were separated from the wastewater and the removal degree of compounds was determined by means of Equation (1).

$$R = \frac{(C_0 - C_k)}{C_0}\ 100 \qquad (1)$$

where: R – the removal degree of chemicals [%], C_0 and C_t – the initial and final concentration of chemicals, respectively [μg/L].

Simultaneously the blank determination was performed according to the same instructions, excluding the dosage of sorbents. The above operation was done to check the potential decay or accumulation of chemicals on the glass or filters, which could provide erroneous experimental data. In order to determine the effect of the solution pH on the adsorption of compounds, the pH was adjusted in the range of pH 3–9 using 1 M solution of NaOH and HCl. This experiment was performed according to the above procedures.

2.3. Sorption kinetics

Kinetic experiments were carried out in glass flasks containing 50 mL of working solution. The initial concentration of chemicals in synthetic wastewater was 500 μg/L and the sorbent dose was equal to 100 mg/L. The flasks were shaken at 200 rpm/min for 4 hours under ambient conditions (23±1 OC). At the predetermined time intervals, the samples were filtered (0.45 μm PTFE filter) in order to separate the sorbents from the wastewater. The amount of chemicals absorbed on the sorbents was calculated according to Equation (2):

$$Q_t = \frac{(C_0 - C_k)\,V}{m} \qquad (2)$$

where: Q_t – the adsorbed amount of adsorbate at predetermined time intervals [mg/g], C_0 – the initial concentration of adsorbate [mg/L], C_t – concentration of adsorbate at predetermined time intervals [mg/L], m – the mass of sorbent [g], V – the volume of the solution [L].

The concentration of chemicals in the samples taken at predetermined time intervals was determined using solid phase extraction followed by HPLC analysis according to the methodology described in the previous work (*Bohdziewicz et al., 2015*).

In order to determine the adsorption kinetics of chemicals, the experimental data were analyzed using pseudo-second-order kinetic model, as given in Equations 3.

$$\frac{t}{Q_t} = \frac{1}{K_2(Q_e)^2} + \frac{t}{Q_e} \tag{3}$$

where: Q_e and Q_t – the amount of chemicals adsorbed at equilibrium and at time (t), K_2 is the pseudo-second-order constants. Furthermore, based on the pseudo-second-order model, the half adsorption time ($t_{1/2}$) (Equation 4) and the initial adsorption rate (h) were calculated (Equation 5).

$$t_{1/2} = \frac{1}{K_2\, Q_e} \tag{4}$$

$$= K_2 \quad {Q_e}^2 \tag{5}$$

The presented results are the arithmetic average of the four replicates of each experiment. For all the cases the assigned error (estimated based on the standard deviation) did not exceed 5% so the results are presented without marking of the ranges of error.

3 *Results and Discussion*

3.1. Effect of adsorbent dose on removal degree of biologically active substances

Figure 1 shows relation between the dose of activated carbon and degree of biologically active compounds removal. The obtained results indicated that activated carbon SX2 had ideal performance for removal of differential biologically active substances from water samples even in the low dose. For 10 mg/L of adsorbent dose, removal degree exceeded 75% for each compound. The application of increasing SX2 doses to constant compounds initial content in working solution resulted in the obtained additional adsorption sites, therefore their reduction degree was slightly improved. This effect was especially observed for diclofenac, benzo(a)pyrene and anthracene. Moreover, in the case of these compounds, for the 50 mg/L dose, the complete removal was achieved. In contrary, removal degree of PCP seemed to be slightly dependent on the adsorbent dose. This effect can be explained by the differential affinity of these compounds to adsorption onto porous structure of the activated carbon. Affinity to adsorption can be described by Log Kow. When the value of Log Kow is lower than 2, the compound is hydrophilic, and the higher is the Log Kow value is, the more hydrophobic is the substance and it exhibits increasing sorption affinity (*Bellona et al. 2004; Wang et al. 2010; Yang and Xing 2007)*. As it could be seen in Table 1, among the selected compounds, the value of Log Kow for PCP was the lowest.

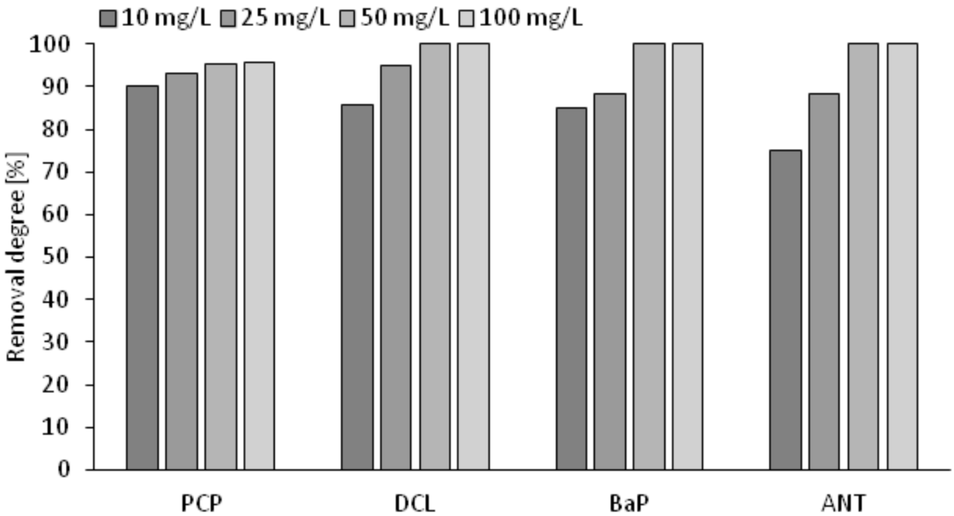

Fig. 1. Effect of adsorbent dose on removal degree of biologically active substances

3.2. Effect of initial concentration of biologically active substances on removal degree

Figure 2 shows that removal degree of the PCP and DCL increased with the increase in the initial concentration. The C_0 provides provided the necessary driving force to overcome the mass transfer resistance of compounds between the aqueous phase and the solid phase. The increase in C_0 also enhanced the interaction between adsorbate molecules and the available sorption sites on the SX2 and the surface functional groups. Therefore, an increase in C_0 improved the uptake of the both adsorbates. It is well visible, especially for the diclofenac at activated carbon dose of 10 mg/L. When the initial concentration was 100 μg/L the removal degree reached 5%, while for 5 times higher C_0 the removal degree exceed 85%. The similar results were obtained by Suresh et. al in (*2011*) in the adsorption of resorcinol and catechol by granulated activated carbon.

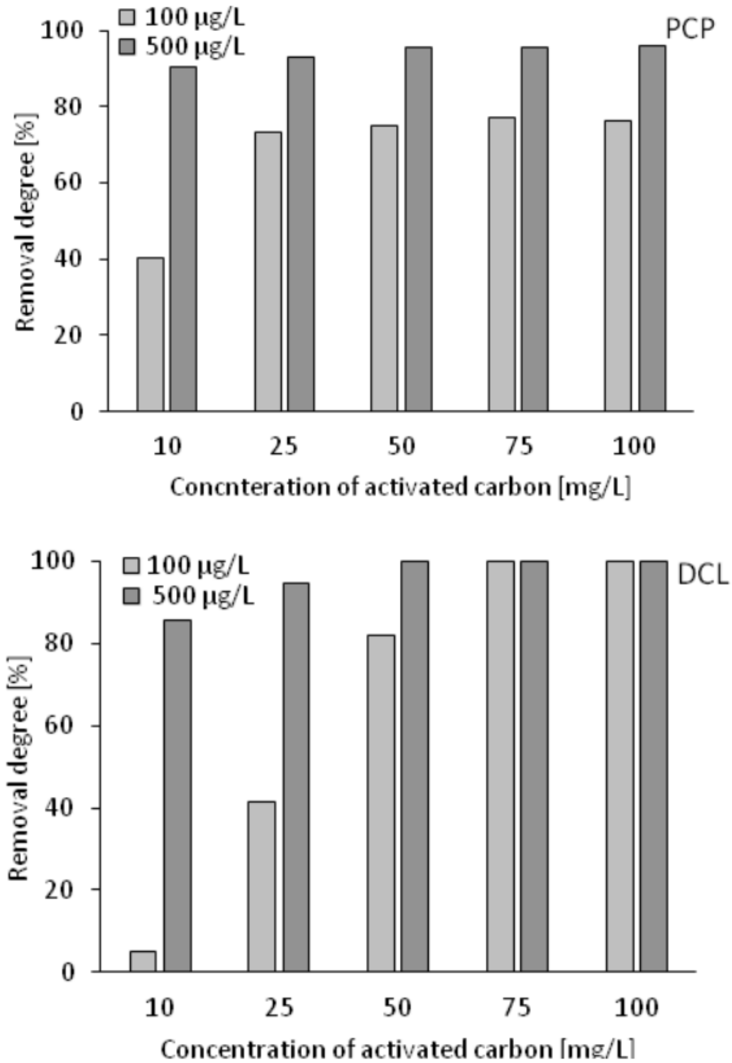

Fig. 2. Effect of initial concentration of PCP and DCL on their removal degree in sorption by activated carbon

3.3. Effect of temperature of sorption on removal degree of biologically active substances

Fig. 3 shows effect of temperature on the removal degree of BaP and ANT. These data unequivocally indicate that increase in the temperature caused increase in the removal degree, especially in case of BaP between temperature 20°C and 35°C. In major paper, adsorption is irreversibly proportional to temperature, that is indicator of physical sorption *(Delle-Site, 2001)*. On the other hand, in this case, both PAHs were adsorbed under the competitive conditions, which can affect the hydrophobic interaction between both adsorbates. However, to better understand the sorption behaviour of PAHs on dependence of temperature further studies will be carrying executed.

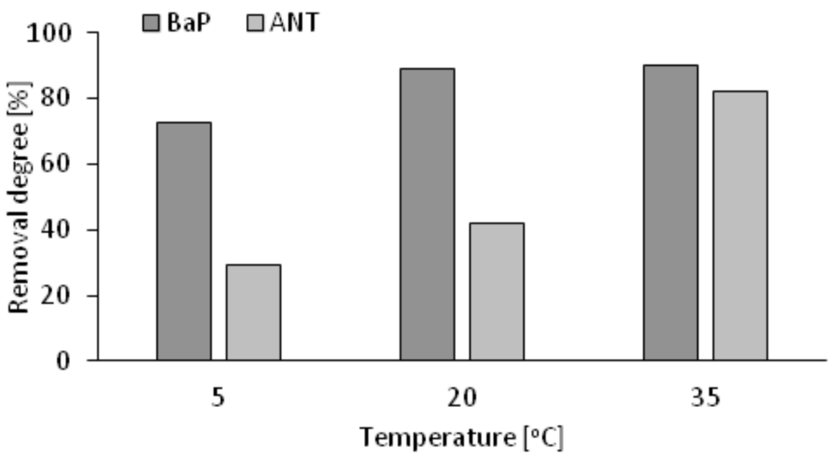

Fig. 3. Effect of temperature of sorption on removal degree of biologically active substances

3.4. Effect of pH of working solution on removal degree of biologically active compound

The pH of deionized water solution is an important factor affecting the sorption process because of its influence on the stability and chemical form of chemicals and also on the surface characteristics of sorbent. This investigation was performed only for the case of adsorption of PCP on SX2 (Fig. 4). It was found that the maximum removal degree of PCP was reached at pH 5 and it decreased progressively with the increasing pH. On the one hand the different functional groups appeared on the surface of carbonaceous sorbent appear different functional groups. Depending on pH, the protonation and deprotonation of surface functional groups affected a different charge of the activated carbon. As some authors suggested, in the acidic environment, the functional groups of activated carbon functional groups have already converted in acidic radicals, that had less electricity as they barely dissociated, and demonstrated weak hydrophilicity, nevertheless, in alkaline conditions, the acidic groups of activated carbon reacted with hydroxyl, so some of the sorption capacity, which caused by the surface functional groups, respectively dropped. On the other hand, the PCP as a hydrophobic weak organic acid with p*K*a = 4.75 appears as either a neutral or an ionized form. The ratio of both PCP species changed with the pH values. More specifically, neutral form of PCP constituted more than 99% of all the PCP at pH 4, and only 5% when pH was than 6. Additionally, the neutral form of PCP was strongly hydrophobic and highly sorptive, and affinity with solid particles of PCP became the highest at pH similar to pKa. It is why the sorption capacity increased from pH 3 to pH 5, but decreased when the pH value was above 5 in the presented experiment.

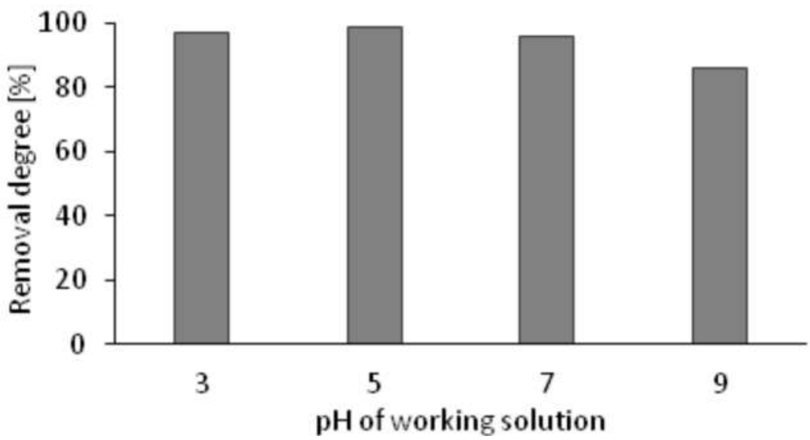

Fig. 4. The effect of wastewater pH on the sorption capacity of PCP on SX2

3.5. Comparison of kinetics of micropollutants on carbon nanotubes and activated carbon

Fig. 5 shows the adsorption of PCP on carbon nanotubes and activated carbon versus time. The kinetic equilibrium for the SWCNT established very quickly, after about 5 minutes, while in terms of SX2 the equilibrium was achieved after 30 minutes.

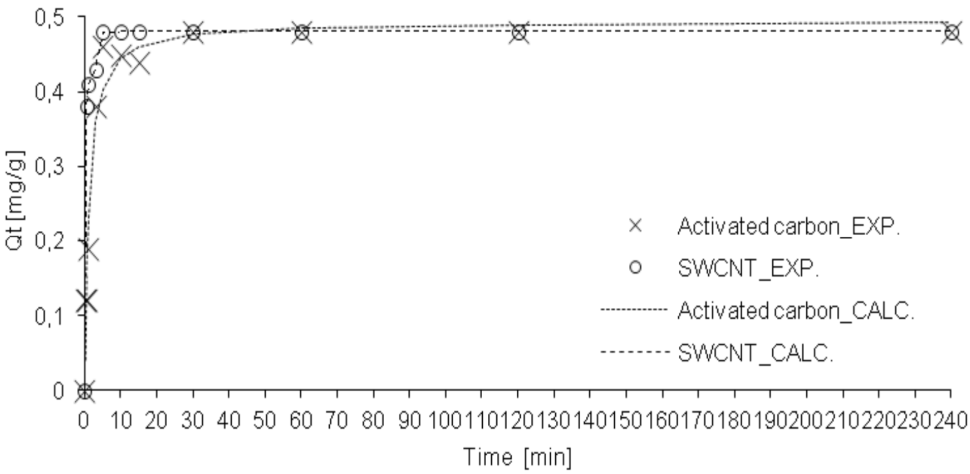

Fig. 5. The effect of time on adsorption of PCP on SX2 and SWCNT

From pseudo-second-order kinetic model, the kinetic parameters were determined (Tab. 2). Both from Fig 5 and on the basis of the value of constant (K_2), half adsorption time ($t_{1/2}$) and the initial adsorption rate (h), the result was that the adsorption process of on SWCNT proceeded very effectively and with the higher rate. More specifically, this effect was mainly connected with the another type of surface sorption. In the case of activated carbon sorption surface possess their microporous structure, in which particles of adsorbate are transported through the macro- and mesopores. In turn the predominantly the external surface of carbon nanotubes is a surface is in which the particles of adsorbate are in direct contact.

Table 1. Fitted parameters using pseudo-second-order kinetics model for sorption of PCP by carbon nanotubes and activated carbon

Sorbent	Parametr					
	K_2 [g/(mg·min)]	$Q_{t(exp.)}$ [mg/g]	$Q_{t(cal.)}$ [mg/g]	$t_{1/2}$ [min]	[mg/(g·min)]	R^2
SWCNT	14.03	0.48	0.4804	0.15	3.24	0.99
Activated carbon	1.79	0.48	0.4943	1.12	0.43	0.96

3.6. Comparison of sorption kinetic of BaP under competitive and uncompetitive conditions

As seen in Figure 6 and in Table 3, adsorption of BaP proceeded more intensive under the competitive conditions than uncompetitive. More specific, in the case of the competitive sorption, initial adsorption rate was about 7 times higher than for uncompetitive conditions. Similarly, K_2 and $t_{1/2}$ were higher when BaP was adsorbed from two component solution. We can assume, that occurrence of ANT enhances sorption of BaP by delivery of the additional driving force to overcome the mass transfer resistance of BaP between the aqueous phase and the solid phase. Moreover, comparing adsorbed amount of BaP and kinetics its sorption, with relevant data for PCP, it is evident that sorption of these two compounds did not demonstrate the same trend. In order to better understand the sorption of organic compounds with different properties the further studies are required.

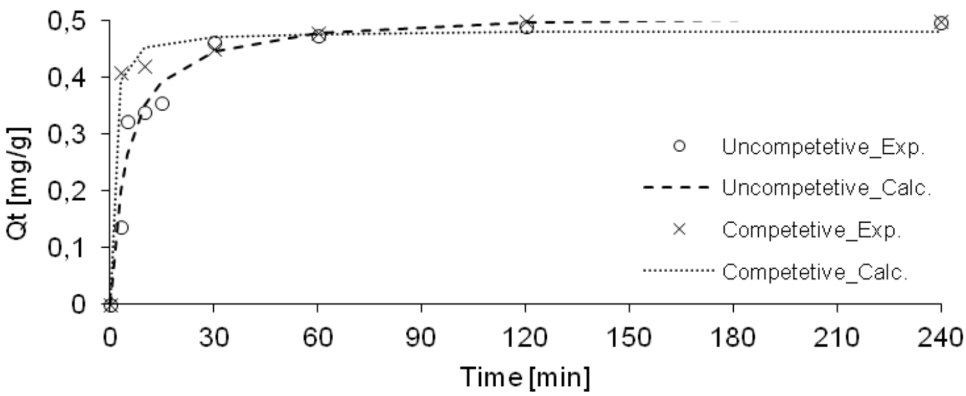

Fig. 6. Comparison of sorption kinetic of BaP under competitive and uncompetitive conditions

Table 2. Fitted parameters using pseudo-second-order kinetics model for sorption of BaP by activated carbon under competitive and uncompetitive conditions

Sorption	Parametr					
	K_2 [g/(mg·min)]	$Q_{t(exp.)}$ [mg/g)	$Q_{t(cal.)}$ [mg/g]	$t_{1/2}$ [min]	[mg/(g·min)]	R^2
Uncompetetive	0.4	0.49	0.52	4.75	0.10	0.96
Competetive	3.1	0.48	0.50	0.66	0.73	0.98

4 Summary and Conclusions

Based on the carried out experiments, it can be concluded that:

Activated carbon SX2 has the ideal performance for the removal of differential biologically active substances from water samples even in the low dose. For 10 mg/L of adsorbent dose, the removal degree exceeded 50% for each compound.

Removal degree of PCP and DCL increases with an increase in the initial concentration. The C_0 provides the necessary driving force to overcome the mass transfer resistance of compounds between the aqueous phase and the solid phase. The increase in C_0 also enhances the interaction between the adsorbate molecules and the available sorption sites on the SX2 and the surface functional groups. Therefore, an increase in C_0 improved the uptake of the both adsorbates

The maximum removal degree of PCP was reached at pH 5 and decreased progressively with the increasing pH.

Increase in the temperature causes increase in the removal degree, especially in the case of BaP, when observed temperature changed from 20°C to 35°C.

Based on value of constant (K_2), half adsorption time ($t_{1/2}$) and the initial adsorption rate (h) was found that, the adsorption process of PCP on carbon nanotubes proceeded very effectively and with the higher rate on the SWCNT than on SX2.

Acknowledgments

The paper was prepared within the frame of the National Science Centre project based on decision no DEC-2013/11/B/ST8/04391.

References

1. Bellona C., Drewes J.E., Xu P., Amy G., Factors affecting the rejection of organic solutes during NF/RO treatment – a literature review. *Water Research*, 38, 2795–2809, 2004.

2. Bohdziewicz J., Kamińska G.: Evaluation of effectiveness of bisphenol A removal on domestic and foreign activated carbons. Ecological Chemistry and Engineering S, 20, 371–379, 2013 a.

3. Bohdziewicz J., Kamińska G.: Kinetics and equilibrium of the sorption of bisphenol A by carbon nanotubes from wastewater. *Water Science and Technology*, 68, 1306–1314, 2013 b.

4. Bohdziewicz J., Kudlek E., Dudziak M.: Fotokataliza/sorpcja/nanofiltracja jako sekwencyjny układ oczyszczania wody zawierającej mykoestrogeny. *Instal*, 2, 62–65, 2014 (in Polish).

5. Bohdziewicz J., Dudziak M., Kudlek E., Kamińska G.: Toksykologiczna ocena procesu fotolitycznego oczyszczania strumieni wodnych zawierających wybrane substancje priorytetowe oraz związki farmaceutyczne. *Inżynieria i Aparatura Chemiczna*, 54, 67–68, 2015.

6. Delle-Site A.: Factors affecting sorption of organic compounds in natural sorbent/water systems and sorption coefficient for selected pollutants. A review. *The Journal of Physical Chemistry A*, 30, 187–439, 2001.

7. Directive 2008/105/WE of the European Parlament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy, amending and subsequently repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC of the European Parliament and of the Council.

8. Dudziak M., Bodzek M.: Usuwanie mikrozanieczyszczeń estrogenicznych z roztworów wodnych w wysokociśnieniowych procesach membranowych. *Ochrona środowiska*, 3, 33–36, 2009 (in Polish).

9. Dudziak M.: Retention of mycoestrogens in nanofiltration. Impact of feed water chemistry, membrane properties and operating process conditions. *Environment Protection Engineering*, 38, 5–17, 2012.

10. El-Naas M., Al-Zuhair S., Abu Alhaija M.: Removal of phenols from petroleum refinery wastewater through adsorption on date-pit activated carbon. *Chemical Engineering Journal*, 162, 997–1005, 2010.

11. Fernandez M., Ikonomou M., Buchanan I.: An assessment of estrogenic organic contaminants in Canadian wastewaters. *Science of The Total Environment*, 373, 250–269, 2007.

12. Ge J., Cong J., Sun Y., Li G., Zhou Z., Qian C., Liu F.: Determination of endocrine disrupting chemicals in surface water and industrial wastewater from Beijing, China. *Bulletin of Environmental Contamination and Toxicology*, 84, 401–405, 2010.

13. Gibson R., Becerril-Bravo E., Silva-Castro V., Jiménez B.: Determination of acidic pharmaceuticals and potential endocrine disrupting compounds in wastewater and spring waters by selective elution and analysis by gas chromatography-mass spectrometry. *Journal of Chromatography*, 1169, 31–39, 2007.

14. Jiang J., Yin Q., Zhou J., Pearce P.: Occurrence and treatment trials of endocrine disrupting chemicals (edcs) in wastewaters. *Chemosphere*, 61, 544–550, 2005.

15. Kamińska G., Bohdziewicz J., Calvo J.I., Prádanos P., Palacio L., Hernández A.: Fabrication and characterization of polyethersulfone nanocomposite membranes for the removal of endocrine disrupting micropollutants from wastewater. Mechanisms and performance. *Journal of Membrane Science*, 493, 66–79, 2015.

16. Lee H., Peart T., Cris G., Chan J.: Endocrine-disrupting chemicals in industrial wastewater samples in Toronto, Ontario. *Water Quality Research Journal of Canada,* 37, 459–472, 2002.

17. Long R., Yang R.: Carbon nanotubes as superior sorbents for dioxin removal. *Journal of the American Chemical Society*, 123, 2058–2059, 2001.
18. Martínez-Zapata M., Aristizábal C., Peñuela G.: Photodegradation of the endocrine-disrupting chemicals 4n-nonylphenol and triclosan by simulated solar UV irradiation in aqueous solutions with Fe(III) and in the absence/presence of humic acids. *Journal of Photochemistry and Photobiology A: Chemistry*, 251, 41–49, 2013.
19. Musbah I., Cicéron D., Saboni A., Alexandrova S.: Retention of pesticides and metabolites by nanofiltration by effects of size and dipole moment. *Desalination*, 313, 51–56, 2013.
20. Nakada N., Tanishikma T., Shinohara H., Kiri K., Takada H.: Pharmaceutical chemicals and endocrine disrupters in municipal wastewater in Tokyo and their removal during activated sludge treatment. *Water Research*, 40, 3297–3303, 2006.
21. Patiño Y., Díaz E., Ordóñez S.: Performance of different carbonaceous materials for emerging pollutants adsorption, *Chemosphere*, 119, 124–130, 2015.
22. Suresh S., Srivastava V., Mishra I.: Study of catechol and resorcinol adsorption mechanisms through granular activated carbon. *Separation Science and Technology*, 46, 1750–1766, 2011.
23. Upadhyayula V., Deng S., Mitchell M., Smith G.: Application of carbon nanotube technology for removal of contaminants in drinking water: a review. *Science of the Total Environment*, 408, 1–13, 2009.
24. Vela N., Martínez-Menchón M., Navarro G., Pérez-Lucas G., Navarro S.: Removal of polycyclic aromatic hydrocarbons (pahs) from groundwater by heterogeneous photocatalysis under natural sunlight. *Journal of Photochemistry and Photobiology A: Chemistry*, 232, 32–40, 2012.
25. Wang X., Liu Y., Tao S., Xing B.: Relative importance of multiple mechanisms in sorption of organic compounds by multiwalled carbon nanotubes. *Carbon*, 48, 3721–3728, 2010.
26. Water Frame European Directives 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water Policy.
27. Yang K., Xing B.: Desorption of polycyclic aromatic hydrocarbons from carbon nanomaterials in water. *Environmental Pollution*, 145, 529–537, 2007.

Biological treatment intensification of food industry wastewater

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Abstract

The food industry is one of the leading branch of Ukraine's economy. It is characterized by using a large amount of water per unit of production and the formation of highly concentrated wastewater. The wastewater often has a pH beyond the recommended range of 6.5–8.5 and can have significant concentrations of fats and demands adjusting the content of nutrients. Considering the ability for biological decomposition of organic pollutions and technological, economic and ecological advantages the crucial role in the prevention of water pollution by food industry wastewater is being played by aerobic biological treatment methods. Biological treatment intensification of food industry wastewater can be achieved by effective preliminary treatment, and by developing the new efficient equipment and biological wastewater treatment technologies. For preliminary wastewater treatment of meat processing plant and concentrate apple juice production plant were applied combined settlers-flotators with diameter of 7.2 m providing the removal of suspended solids by an average of 80%, fats (for meat processing) - an average by 85%, reducing the concentration of organic pollutants by COD - an average of 56 %. Increasing of activated sludge concentration is usually achieved by applying surface-jet aeration tanks with large hydraulic height combined with peripheral secondary settlers. Industrial research of such aeration tanks-settlers of 10.0–15.0 meters in diameter and 7.0–9.0 meters in hydraulic height were performed in the following companies: meat and dairy processing plants, the production of concentrate apple juice, corn starch and caramel syrup. During wastewater treatment before being discharged into municipal sewage system or on the first stage of biological treatment provided reduction of COD - an average of 83.6% and BOD_{20} - by 95.5%. The maximum concentration of activated sludge in the aeration zone was 7.1 g/dm^3 and oxidizing power for BOD_{20} - 6850 g/(m^3 day). The observed efficiency of ammonia nitrogen removal by simultaneous nitrification-denitrification was 84.4% or 90.8 g/(m^3 day).

Keywords

food processing wastewater, settlers-flotators, aeration tanks-settlers of large hydraulic height, a simultaneous nitrification-denitrification

1 Introduction

The food industry is one of the leading industries of Ukraine and is developing very dynamically. In Ukraine`s food industry participate over 22 thousand companies employing more than 1 million people, and its share in total industrial production reaches value of 15–21%.

Food industry including milk and meat industry, poultry meat, fats, starches, fruits and vegetables, sugar, cereals and others that are sources of many impacts and threats to the natural environment. Problem of environmental protection in the food industry concerning mainly wastewater treatment and are caused, first of all, the quality and quantity of wastewater.

Processing of food is characterized by a high water use and, as a result, significant quantities of wastewater, appearing at different stages of the process, for example, during washing and processing of raw materials, washing equipment. The quantity and type of wastewater is largely predetermined by branch of industry, technology and seasonality production as well as the quantity of water consumed.

Wastewater from the food industry is characterized by high concentrations of BOD_5, fats, suspended solids and variable pH *(Bartkiewicz and Umiejewska 2010; Carawan, 1979; Chen and Lo, 2003; Ersahin et al., 2010; European Commission, 2006; Kasapgil et al., 1994; Kovalchuk et al., 2013; Kovalchuk, 2014; Maly, 1996; Martinez et al., 1995; Rosenwinkel et al., 2005)*.

Obviously the simplest criterion of biooxidation of wastewater organic pollutions is the experimental determination of the BOD. If this value is determined (i.e. oxygen consumption occurred), then the pollutions referred to as biologically oxidizing. The measure of biooxidation of organic pollutions numerically Is estimated by the ratio of BOD_{20}/COD. If the ratio $BOD_{20}/COD > 0.5$, for neutralization of organic pollutants are useful aerobic biological methods.

Table 1 shows the value of wastewater ratio BOD_{20}/COD for some food plants. For other enterprises wastewaters related BOD_{20}/COD are: 0.71 - fish processing plant; 0.65 - fish cannery; 0.71 - sugar factories, 0.53 - the production of alcohol from potatoes; 0.46 - alcoholic beverage production, 0.7 - soft drinks production; 0.68 - canned fruits and vegetables; 0.63 - yeast plants, 0.63 - milling plants. The grade of biooxidation of organic wastewater pollutions can also be estimated from the ratio of BOD_5/COD that is: 0.8 - oil extraction plant; 0.33 - plants for initial winemaking; 0.22 - for the perfume and cosmetic production. From the data we can conclude that the vast majority of food industry wastewater (except for perfume and cosmetic production, salt industry, etc.) can be treatment by biological methods.

Considering the ability for biological decomposition of organic pollutions and technological, economic and ecological advantages, the crucial role in the prevention of water pollution by food industry wastewater is played by aerobic biological treatment methods. It is therefore important to intensify the existing and to develop new effective structures and technologies for preliminary and biological wastewater treatment.

Table 1. Characteristics of food industry wastewater (*Kovalchuk, 2013; Kovalchuk et al., 2015*)

Parameter	The values of wastewater pollutants concentrations for enterprises				
	Meat processing plant	Poultry processing plant	Dairy processing plant	Concentrated apple juice production plants	Corn starch and caramel syrup producing plant
pH	6.2–7.6	6.8–7.0	3.7–9.8	4.5–10	4.7–7.4
TSS [mg/dm^3]	1793	6235	493	1464	831
COD [mg/dm^3]	3430	6687	4116	7413	941
BOD_{20} [mg/dm^3]	1788	4682	3547	5145	650
BOD_5 [mg/dm^3]	1697	2639	3335	3705	518
Ammonia nitrogen [mg/dm^3]	178	77	7.2	14	6
Phosphates [mg/dm^3]	128	175	210	2	-
Fats [mg/dm^3]	483	1341	66	-	-
BOD_{20} / COD	0.52	0.70	0.86	0.69	0.69
BOD_{20} / N	100/7.7	100/1.3	100/0.2	100/0.2	100/0.7
BOD_{20} / P	100/3.5	100/1.8	100/2.8	100/0.01	100/-

Discharge of the treated food industry wastewater in Ukraine into urban sewage systems is acceptable due to degree of incomplete biological treatment. However, its effectiveness must be established, based on the need for biological nitrification of ammonia nitrogen (residual concentration of 2.5–35 mg/dm^3) and oxidation of emulsed fats (residual concentration of 4.4–50 mg/dm^3). Municipal companies strict requirements on the content nitrites (in some cases - up to 0.01 mg/dm^3) and nitrates (in some cases - up to 5 mg/dm^3) in the treated wastewater point to the need for biological denitrification processes. In the case of discharge into open waters, it is necessary to provide the full biological and tertiary wastewater treatment degree with ensuring additional Ukrainian law requirements to the treatment effectiveness of next indicators: ammonia nitrogen content (up to 0.5–1 mg/dm^3), nitrites (up to 0.01–0.42 mg/dm^3) and nitrates (up to 1–40 mg/dm^3), phosphates (up to 3.12–4 mg/dm^3) and iron (up to 0.18–0.3 mg/dm^3), petroleum products (to 0.01–0.5 mg/dm^3) and surfactants (0.2 mg/dm^3). Fats in the treated wastewater have to be completely absent.

The efficiency of food industry biological wastewater treatment process depends on the providing of certain fundamental conditions. They concern the uneven inflow of wastewater, nutrients content, the total suspended solids and fats concentrations as well as pH fluctuations.

Food industry enterprises are characterized by a large variability of the quantity and quality of wastewater, thus the equalization of flows is required. However equalization volume in this case is comparable to the volume complete mix aeration tanks that can act as equalizator.

Values of wastewater pH of food industry enterprises depend largely on the type of raw materials applied and the use of alkaline chemicals for washing equipment. For some enterprises it can change in a significant range that goes beyond the recommended by author of this elaboration values for the biological treatment (6.5–8.5), which requires previous adjustment of pH by chemical neutralization. In many cases, adjustment of nutrients contents for normal biological wastewater treatment is required.

The applied primary sedimentation tanks in most enterprises of food industry do not provide the sufficient efficiency of suspended solids and fats removal from wastewater before the biological treatment. This necessitates the use of flotation, which provides significantly higher effectiveness of suspensions, emulsions and colloids parts removal, thus intensifying biological wastewater treatment.

For a preliminary removal of suspended solids and fats from wastewater proposed in this elaboration a new combined structure - settler-flotator, the development of which advantages and disadvantages of grease traps, settlers and flotators were taken into account. Settler-flotator is a vertical type flotation cell in which wastewater is first exposed to short-term sedimentation, then undergoes pressure flotation with recirculation. This allows:

- to increase the overall efficiency of suspension removal from wastewater by the preliminary sedimentation of the largest, poorly flotating, particles;

- providing the most effective contact between solids and air bubbles during their vertical movement;
- to simplify the process of removing sludge and sediments.

One of the most effective methods of increasing the oxidizing power of aeration tanks is to increase the mass of sludge involved in wastewater treatment process.

Increase of the activated sludge mass can be achieved by three methods. The first method is carried out in aeration tanks with fixed or moving bed to increase the concentration of biomass. The second method provides sludge mixture separation on special filter partitions or membranes. The third method involves the separation of concentrated sludge mixture by thin-layer sedimentation tanks, pressure flotation cells or applying secondary settling tanks large hydraulic height.

The growth of the sludge mass requires an increase in oxygen supply in the aeration tanks for the needs of endogenous respirations.

Aerators of high oxidizing ability can be used in the aeration tank with a high concentration of activated sludge - mechanical, pneumatic-mechanical and jet aerators. However, mechanical and pneumatic-mechanical aerators have significant disadvantages:

- insufficient degree of mixing volume of aeration zone;
- limited capacity of the working area of single aerator;
- special equipment requirement to service the aerators;
- low reliability because of possible damage to the engine or gearbox;
- possible water pollution by grease lubrication.

The main disadvantages of jet aerators are small penetration depth in sludge mixture flow of the working liquid captured air bubbles. However, the rational organization of flow in jet aeration tank can successfully provide mixing sludge, as evidenced by their positive experience with long-term use in many wastewater treatment plants.

For biological removal of nitrogen and phosphorus multipurpose devices are currently used, containing anaerobic, aerobic and anoxic zones operating by known technologies. However, the use of anaerobic zones in biological wastewater treatment facilities can lead to unpleasant odors, which is unacceptable in the food industry. Therefore, it is advisable to remove phosphates in the wastewater treatment using reagents.

For biological wastewater treatment of food industry aeration tanks of large hydraulic height (8–10 m) with the surface jet aeration, combined with peripheral secondary settling tanks were proposed (Fig. 1) *(Kovalchuk et al., 2010; Kovalchuk, 2013a)*. Their application provides the following advantages:

– biological wastewater treatment at high doses of activated sludge and its effective separation from treated wastewater performed in one facility;
– the use of jet aeration system provides high oxidizing ability and significant efficiency of aeration;
– due to the continuous sampling a sludge mixture from the bottom and feed on the surface jet aerators, sludge recirculation will be provided and downward movement of sludge mixture appears in the aeration zone;
– in the bottom of the aeration zone due to the gradual reduction of dissolved oxygen in biological processes the anoxid zone is being formed, providing the ability to simultaneous nitrification-denitrification.

Filters with floating bed of polystyrene can be used for tertiary wastewater treatment of food industry.

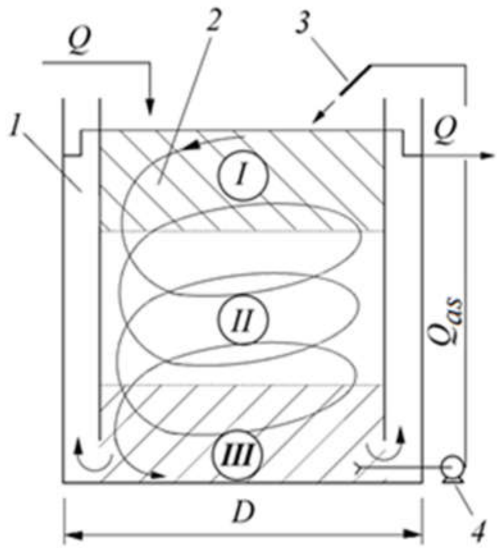

Fig. 1. Diagram of aeration tank with large hydraulic height and the surface jet aeration, combined with peripheral secondary settling tank: 1-secondary settling tank; 2-aeration tank; 3-jet aerator; 4-jet aerator pump; I-aeration zone; II-zone of reducing dissolved oxygen concentration (transitive zone); III-anoxic zone

2 *Materials and Methods*

The research of work efficiency of aeration tanks with large hydraulic height was carried out on wastewater treatment plant in the meat (Fig. 2) and dairy processing plants (Fig. 3), concentrate apple juice production plant (Fig. 4), corn starch and caramel syrup production plant (Fig. 5), that were built on assumption of developed technology presented in this paper.

Fig. 2. Wastewater treatment plant of meat processing plant “Rhythm” in Chernihiv, Ukraine

Fig. 3. Wastewater treatment plant of dairy processing plant in Shostka, Ukraine

Fig. 4. Wastewater treatment plant of concentrate apple juice production plant in "Bukofruit" company

Fig. 5. Wastewater treatment plant of corn starch and caramel syrup production plant

For removal of large solid particles from wastewater, it was used screens (at concentrate apple juice production plant - arc sieve), for sand and other large mineral impurities removal – horizontal flow or vortex-type grit chambers were applied.

Settlers-flotators diameters of 7.2 m were built in wastewater treatment plants at meat processing and concentrate apple juice production plant. Before biological treatment nitrogen and phosphorus salts were added in case of wastewater from corn starch and caramel syrup production plant, and the wastewater from concentrate apple juice production plant alkaline chemicals were supplemented for neutralization

Food industry wastewater biological treatment was carried out in the aeration tank diameter and hydraulic height respectively: 10 and 8.5 m - meat processing plant “Rhythm” in Chernihiv, Ukraine (discharge of treated wastewater into the municipal sewers, the plant 1 in Table 2); 10 and 8.5 m - for the Shostka, Ukraine milk processing plants (discharge of treated wastewater into municipal sewers, the plant 2 in Table 2); 10.0 and 9.0 m - for concentrate apple juice production plant “Bukofruit” company (at the first stage, the discharge of treated wastewater into surface water, the plant 3 in Table 2); 15.0 and 8.0 m - for corn starch and caramel syrup production plant (at the first stage, the discharge of treated wastewater into surface water, the plant 4 in Table 2).

3 *Results and Discussion*

During the execution of research there were established parameters and efficiency of food industry biological wastewater treatment in the aeration tank with large hydraulic height (Table 2).

Preliminary wastewater treatment by flotation significantly reduces the load on aeration tanks and significantly increases the efficiency of biological treatment. Without the use of any coagulants and flocculants efficiency removal of suspended solids and fats from meat processing plants wastewater amounted to 35.5–85.8 and 65.6–87.8%, respectively. The average residual concentration of suspended solids and fats did not exceed, respectively, 246 and 74 mg/dm^3. At the same time wastewater COD reduction was 39.5–76.0% (average 57.8%), BOD_5 - 43.7–63.8% (average 52.8%), BOD_{20} – 41.8–74.2% (average 53.3%). Using settlers-flotators for concentrate apple juice production wastewater treatment provided a reduction of suspended solids concentrations (average value) - by 82.3%, COD – by 56.6%; BOD_{20} - by 46.0%, and BOD_5 - by 47.7%.

As a result, industrial research of aeration tanks with large hydraulic height allowed observation that the maximum F/M ratio at which the full biological wastewater treatment was achieved was equal to 260 mg BOD_{20}/d per g MLVSS. For F/M ratio less than 500 mg BOD_{20}/d per g MLVSS the noted biological treatment efficiency was 92–99%, while the F/M ratio is big (more than 500) - reduced to 80–98%.

By increasing the F/M ratio above 400 and decreasing below 150 mg BOD_{20}/d per g MLVSS, sludge volume index increased without exceeding the value of 131 cm^3/g, which indicated its satisfactory sedimentation properties.

Table 2. The results of biological wastewater treatment in the aeration tank with large hydraulic height *(Kovalchuk, 2013b, Kovalchuk et al., 2015)*

Parameter		The values of wastewater pollutants concentrations for enterprises			
		1*	2	3	4
pH	b	6.41–7.27 6.81	4.18–6.37 5.56	4.45–5.78 5.11	4.71–7.37 6.31
	a	6.50–8.15 7.37	7.12–7.74 7.38	6.35–7.39 7.00	7.43–7.85 7.70
TSS [mg/dm^3]	b	122–590 326	248–867 493	177–430 296	145–1528 586
	a	5.2–44 23	194–345 257	74–167 125	2–49 16
COD [mg/dm^3]	b	637–2828 1463	910–6664 4116	2822–3205 3022	696–7330 2424
	a	85–445 248	45–739 231	129–604 312	27–108 76
BOD_{20} [mg/dm^3]	b	406–1795 1040	760–4508 3547	2405–2872 2563	453–5505 1787
	a	10–104 39.8	12.5–613 58	335–542 127	8.5–36 14
Ammonia nitrogen [mg/dm^3]	b	72–310 188	5.8–8.8 7.2	1.4–58 23.2	0.5–45 8.2
	a	0–30.3 14.2	0–0.87 0.48	0–5.9 2.1	-
Nitrate (N) [mg/dm^3]	a	0–39.5 20.1	-	-	0.73–23.3 11.8
Phosphate [mg/dm^3]	b	36–203 118.8	49–295 210	0–125 65.1	-
	a	0–18 3.75	0–61.3 21.9	0–15 7.9	-
Fats [mg/dm^3]	b	50–108 67	-	-	-
	a	5.3–34.3 18.4	-	-	-

Minimum and maximum value in the ranges and mean value below the ranges: b – before treatment; a – after treatment.

* Number nit hic row are coherent with description of companies presented in chapter materials and methods.

Increasing the concentration of activated sludge in the aeration zone did not result in a significant increase in the removal of sludge from secondary settling tanks. For example, increasing the concentration of activated sludge in the aeration tank of one of the meat processing plants to 7.1 g/dm^3 allowed for increasing oxidizing power for BOD_{20} to 6850 g/(m^3 d), and removal of sludge from secondary settling tanks not exceed 229 mg/dm^3, which allows to qualify for the discharge of treated wastewater into municipal sewers.

The calculation of the material balance of nitrogen in meat processing plant wastewater confirmed the possibility of implementing simultaneous nitrification-denitrification in aeration tank with large hydraulic height. It was found that in this case through biological nitrification-denitrification 22.0–71.0% of the initial content of ammonia nitrogen was removed for a total reduction of its concentration on 92.4–98.1%. Due to increased F/M ratio the efficiency removal of ammonia nitrogen increased and reached 90.8 g/(m^3 d). The residual concentration of ammonia nitrogen into biologically treated wastewater was equal to 1–14.2 mg/dm^3.

The technology of wastewater treatment was successfully implemented and is used in over thirty food industry enterprises in Ukraine.

4 Summary and Conclusions

1. Wastewater from the food industry presents very highly concentrations of the organic pollutants content, suspended solids (and sometimes fats), that may be adversely for biological treatment from nutrients and negatively influence on pH value. Usually, it does not contain toxic impurities, and regime of their inflows differs considerably uneven.
2. The analysis of organic pollutants biodegradation degree in BOD_{20}/COD ratio showed that wastewater generated in the majority of the food industry enterprises can be treated by biological methods.
3. It was investigated that under production conditions the efficiency of vertical-type settler-flotator, in which wastewater is first exposed to short-term sedimentation then to the pressure flotation with effective contact between solids and air bubbles during their joint vertical movement. This increases the biological treatment rate by effectively removing suspended solids (average 80%) and fat (for meat processing plants average 85%) and causes decrease in concentration of organic wastewater pollutions (COD average of 56%).

There was developed, for food industry biological wastewater treatment, the construction of aeration tanks with large hydraulic height with surface jet aeration, combined with peripheral secondary settling tanks operating at higher activated sludge concentrations and with an increased oxidizing power. While wastewater treatment before discharge into municipal sewers or use at the first stage of the biological treatment providing reduction of COD - an average of 83.6% and BOD_{20} - by 95.5%. The efficiency of ammonia nitrogen removal by simultaneous nitrification-denitrification was observed as reaching 84.4% or 90.8 g/(m^3 d).

References

1. Bartkiewicz B., Umiejewska K.: Oczyszczanie ścieków przemysłowych (Treatment of industrial wastewater). Wydawnictwo Naukowe PWN, Warszawa 2010.
2. Carawan R.E. Water and wastewater management of food processing. Spinoff on meatprocessing water and wastewater management. Extension special report № AM18c. The north California agricultural extension service, 1979.
3. Chen C.-K., Lo S.-L. Treatment of slaughterhouse wastewater using an activated sludge/contact aeration process. *Water Science and Technology*, 47 (12), 285–292, 2003.
4. Ersahin M. E., Ozgun H., Dereli R. K. and Ozturk I.: Anaerobic treatment of industrial effluents: an overview of applications. INTECH Open Access Publisher, 2011. www. intechopen.com/books/waste-water-treatment-and-reutilization/anaerobic-treat-ment-of-industrialeffluents-an-overview-of-applications
5. European Commission. Integrated Pollution Prevention and Control Reference Document on Best Available Techniques in the Food, Drink and Milk Industries. 2006. www.eippcb.jrc.ec.europa.eu/ reference/BREF/fdm_bref_0806.pdf.
6. Kasapgil B., Anderson G. K., Ince O.: An investigation into the pre-treatment of dairy wastewater prior to aerobic biological treatment. *Specialised Conference on Pretreatment of Industrial Wastewater. Water Science and Technology*, 9, 201–215, 1994.
7. Kovalchuk V., Kovalchuk A.: Biological wastewater treatment in aeration tanks-settlers with jet aeration. *Installation market*, 5, 11–13, 2010.
8. Kovalchuk V., Kovalchuk A.: Wastewater treatment of concentrate apple juice production plants. *MOTROL. Commission of motorization and energetics in agriculture*, 17 (6), 53–61, Polish Academy of Sciences, Lublin – Rzeszow 2015.
9. Kovalchuk V., Kovalchuk A., Samelyuk V.: Biotechnology of food industry wastewater treatment. *Municipal economy of cities*, 93, 182–187, Kharkiv, 2013.
10. Kovalchuk V.: Wastewater treatment of corn starch and caramel syrup production plant. *Construction Science Bulletin*, 71, 383–387, Kharkiv, 2013.
11. Kovalchuk V.: Food industry’s wastewater treatment. In: Sobczuk H., Zhukova V. (eds.) Pure water. Fundamental, applied and industrial aspects. Proceedings of the II International Scientific and Technical Conference. National Technical University of Ukraine “Kyiv Polytechnic Institute”, 26–29, 8–11 October 2014.

12. Kovalchuk V.: Features of the meat industry wastewater treatment. In: Sobczuk H., Zhukova V. (eds.) Pure water. Fundamental, applied and industrial aspects. Proceedings of the III International Scientific and Technical Conference. National Technical University of Ukraine "Kyiv Polytechnic Institute", 21–24, 28–30 October 2015.
13. Kovalchuk V.: High biooxidizing constructions in the meat and dairy industry wastewater treatment systems. *Construction Science Bulletin*, 60, 247–251, Kharkiv, 2013a.
14. Kovalchuk V.: Settler-flotation units for the meat industry wastewater pre-treatment. *Installation market*, 9, 20–21, 2009.
15. Kovalchuk V.: The technology of wastewater treatment of meat processing plants. *MOTROL. Commission of motorization and energetics in agriculture*, 13 (6), 109–116, Polish Academy of sciences, Lublin – Rzeszow 2013b.
16. Malý J., Hlavinek P.: Čištěni průmyslových odpadních vod . Brno: Noel 2000, 1996.

Water quality analysis in a selected rural water supply system

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Abstract

The maintenance of a required water quality in a water supply system is a difficult and complex issue. Physical, chemical and biological processes occurring during the water's flow through a water supply network depends on many factors. The hazard of the secondary growth of microorganisms in a water environment appears practically always and can cause a water quality worsening. That problem is often observed and hard to solve. The water quality is also directly related to the condition of a water supply network, its realization, exploitation time and conditions, condition of water installations and applied pipe's material. Plastic materials are susceptible to degradation processes due to a loads effecting, temperature or many others environmental factors. In order to counteract the polymer's degradation process, stabilizers of a different kind are added to plastics. These are mainly heat, lead or ultraviolet light radiation stabilizers, plasticizers, separating agents and others. These compounds or products of their degradation can migrate into water contacting with pipe's material, what can influence the quality of a drinking water.

The purpose of this paper is to present results of a water quality analysis in selected rural water supply system, located in a district of a distinctly agricultural character. The whole system was built of unplasticized polyvinyl chloride (PVC-U) material. The paper presents basic chemical and microbiological analysis of water and test of suspended sediment in water. The executed tests included also the influence of pipe's material on the water quality. Analysed water samples were taken from specific sampling points, selected in accordance to a preliminary calibrated numerical model of a considered water supply network.

Obtained test's results revealed that among examined physic-chemical indicators the biggest changes were observed in sampling points of the highest water age. In some samples, the indicators values exceed permissible limits. Obtained numerical values could be burden of a notable calculation error due to the slight weight of materialized sediments.

Keywords

water quality, PVC-U pipes, lead stabilizers, rural water supply systems

1 Introduction

The maintenance of a required water quality in a water supply system is a difficult and complex issue. Physical, chemical and biological processes occurring during the water's flow through a water supply network depend on many factors. Water quality is directly connected with the state of water supply network, its quality, time and conditions of its operation, type of material used, the state of water supply connections and the state of plumbing (*Kulbik, 2004*). Both comfort and health safety of end users depend heavily on the quality of supplied water (*Gato-Trinidad et al,. 2011; Kuś et al., 2003*). Since 1989, there has been a steady decrease of water demand for people and industry, which resulted in deterioration of hydraulic conditions in water networks, observed mainly as considerable decrease of flow velocity in water pipes (*Kowalski et al., 2008; EPA U.S., 2002; Cruickshank, 2010*). Furthermore, lower demand leads to higher water retention time in network: the water age (*Kuś et al., 2001*), which can potentially contribute to water quality deterioration (*Rozporządzenie, 2010; Sokołowska and Oleńczuk-Neyman, 2009*). In addition, providing proper water quality in smaller settlement units, of up to 10,000 inhabitants, is hindered by effective lack of regulations regarding water quality monitoring and the distribution of water sampling points along the system. According to recommendations presented in the Minister of Health Regulation (*Rozpodządzenie, 2010; Rozporządzenie, 2007*) the number of samples should be in the range of 7–34 per year for control and merely 2–5 per year for inspection.

The microbiological quality of water delivered to customers has the greatest importance during the water safety evaluation. The hazard of the secondary growth of microorganisms in a water environment appears practically always (*LeChevallier, 1999*) and can cause a water quality worsening. That problem is often observed and hard to solve (*Sokołowska and Oleńczuk-Neyman, 2009*). Microorganisms in a water supply network can occur as floated with water single cellars or as biological film (biofilm) covering internal surfaces of pipelines or fittings. In drinking water distributions systems presence of biofilm leads to water quality worsening, arouse and intensify corrosion processes and increase disinfectant use (*Traczewska and Sitarska, 2008*). The growth of all microorganisms requires inorganic connections between nitrogen and phosphorus. Heterotrophic organisms require also biodegradable dissolved organic substances, mostly their assimilable fraction (*Volk and LeChevallier, 1999*). The source of nutrients is not only the biologically unstable water pumped into the distribution systems, but also chemical and biological sediments occurring in the system (*Hem and Efraimsen, 2001*) and some plastic materials used for production of pipes (*Lethola et al., 2005, Świderska-Bróż, 2010*). During chlorination, the biggest risk of secondary contamination occurs with the high water retention time and too low concentration of chlorine residual (*Volk and LeChevallier, 1999*).

One of the factors that can influence on the water quality in water supply network is pipe material. The most commonly used material for the production of rural water supply network pipes is unplasticised polyvinyl chloride (PVC-U). Similarly to other plastics, PVC-U is susceptible to degradation in loading, high temperature and other environmental factors. To counteract polymer destruction and to aid its processing, different stabilisers are added, such as heat stabilisers, UV stabilisers, plasticisers, release agents (*Simard et al. 2011; Fisch and Bacaloglu, 1999*). Typical heat stabilisers are cadmium, calcium, barium, strontium, magnesium, zinc or fatty acid salts. The group of lead stabilisers includes sulphates, phthalates or phosphates, such as Interstab L (Akzo-Chemie Interstab) (*Benavides et al., 1996*). These compounds or products of their degradation can migrate into water contacting with pipe's material, what can influence the quality of a drinking water (*Sadiki et al., 1996; Al-Malack, 2001; Al-Malack and Sheikheldin, 2001; Lasheen et al., 2008; Edberg and Allen, 2004*).

The conducted research consisted in water analysis in the selected rural water supply system constructed of exclusively PVC-U materials with particular focus on the impact of plastic material on water quality. The research included chemical and microbiological analysis and tests of suspended deposit. The analysis was conducted on samples obtained from characteristic points determined from a calibrated hydraulic model of the analysed water supply system.

2 Materials and Methods

The analysed water system is located in a district of 5,314 inhabitants and 1,250 farms. The district is of distinctly agricultural character, with agricultural lands covering 76.5%. The percentage share of agricultural lands is as follows: 73.7% arable land, 24.9% grassland (meadow, grazing land), 1.4% orchard and 12% forest. Local Municipal Services Department is responsible for water distribution in the district area, and there are three water distribution zones distinguished in the system. The tests were conducted solely in one of zones, constructed entirely of PVC-U pipes, whose diameter ranges from 63 mm to 160 mm. The total length of network is equal to 32.3 km. The network's underground water intake consists of the main well and the emergency well and two 150 m^3 water containers. Approximately 43,000 m^3 of water is supplied by the network to end users. Daily water usage is between 0.1 m^3/d and 5.21 m^3/d. The highest demand for water is observed in the evening, between 6 and 8 pm, and the lowest between 1 and 3 at night. Schematic representation of the analysed network is presented in Fig. 1. The measuring points were determined from the hydraulic model of the system, created with EPANET 2.0 software, where simulation of water retention time (so-called water age) allowed establishing three points characterised by the longest water age (points 1, 2 and 5). One point was located in the main pipe supplying water to the network (point 3) and one at the pumping station (4). The model consists of 264 nodes and 262 pipes (Fig. 1).

Water analysis

Water samples were obtained from selected measuring points with the use of hydrants, which were flushed for approx. 5 min. Basic water parameters were determined according to standard procedures described in norms. Water conductivity and pH reaction of water were measured with cPC-551 computer, whereas water alkalinity according to standard PN-91 C04540/03, hardness according to PN-ISO 6059:1999, oxidability as per PN-8 C-04578/02 and dry matter according to PN-75 C-04616/01. Ammonium nitrate was determined with Cd8039 reduction method with the use of HACH spectrophotometer, the colour was determined based on The Platinum-Cobalt Scale, whereas turbidity was tested with a turbidometric method with a TN-100 meter.

The growth of microorganisms was evaluated by bacteria number analysis – the general number of mesophilic bacteria (incubation time: 48h, temperature 36±2^{o}C) and psychrophilic bacteria (incubation time: 72h, temperature 22±2^{o}C) using Koch plate method on nutritious agar according to standard PN-ISO 6222. Samples were collected in accordance to PN-EN ISO 5667-3, while bacteria colony counting was pursued by the PN-ISO 8199 procedure. The most probable number (MPN) of Fe(II)iron oxidizing bacteria in 100 cm^3 sample was marked on a Winogradski selective growth medium with ferric-ammonium citrate by standard PN-80/C-0461524. The MPN of sulphate reducing bacteria (Clostridium perfingenes) were marked on liquid growth medium in standard PN-EN 26461-1 methodology. Tests were executed in Laboratory of Environmental Analyses in Faculty of Environmental Engineering, Lublin University of Technology.

After mineralisation of pipe sections extracted from the analysed network, it was concluded that the pipes were stabilised with lead compounds, which is why water analysis, aimed at determining the impact of pipe material on the quality of water in contact, included determination of lead content in water samples. The analysis was conducted with ICP-OES JY238 Ultrace (HORIBA Jobin Yvon, France) spectrometer with plasma emission. The spectrometer was calibrated to the following wavelengths: Cu 324.754 nm, Fe 259.940 nm, Mn 257.610 nm, Pb 220.353 nm. The measurements were conducted using background correction. The calibration curve was adjusted to 4 points, detection limit Max (5/3), integration time 2 s. ICP multi-element standard solution VIII (Merck ICP Standard) calibration solution was used, samples were stabilised in HNO3 (Merck 65% Suprapur®). The spectrometer settings were as follows: Czerny-Turner monochromator, focal length – 1 m, vertical plasma, power – 1kW, Nebulizer gas flow 0.7 l/minute at 2.8 bar, Sample uptake rate 1 ml/min, Nebulizer - MiraMist®, Spray chamber type – cyclonic.

Deposit analysis

Deposit analysis extracted from the analysed water supply network was also conducted with ICP-OES JY238 Ultrace spectrometer, however, tests were conducted with the use of semi-quantitative analysis. The calibration curve was adjusted to 2 points of 0 and 50 mg/dm^3 for all analysed elements, detection limit Max (1/1), integration time 1 s. The simplification of procedure resulted from small deposit amount (30 mg) obtained after mineralisation in HNO_3 in a closed system.

3 Results and Discussion

Results of water samples deposit

Test samples were extracted from the locations marked with numbers in Fig. 1. Basic water quality parameters are shown in Table 1, which additionally collates results of tests conducted by the Municipal Water and Sewerage Company on 05.05.2014. The last column shows acceptable values of parameters obtained from the Minister of Health Regulation (*Rozpodządzenie, 2010; Rozporządzenie, 2007*).

As it can be observed based on the presented results it was colour and turbidity that were subject to the greatest changes. The highest recorded values were obtained at measuring point 2, where the water retention time was equal to 480 h, and was therefore the longest in the entire network. Both the colour of 20 mg Pt/dm^3 and turbidity of 4.45 NTU exceeded limit values described in the Regulation (*Rozpodządzenie, 2010; Rozporządzenie, 2007*). Similarly electrical conductivity and oxidability were on an elevated level. The results are indicative of water contamination with substances of both organic and non-organic origin.

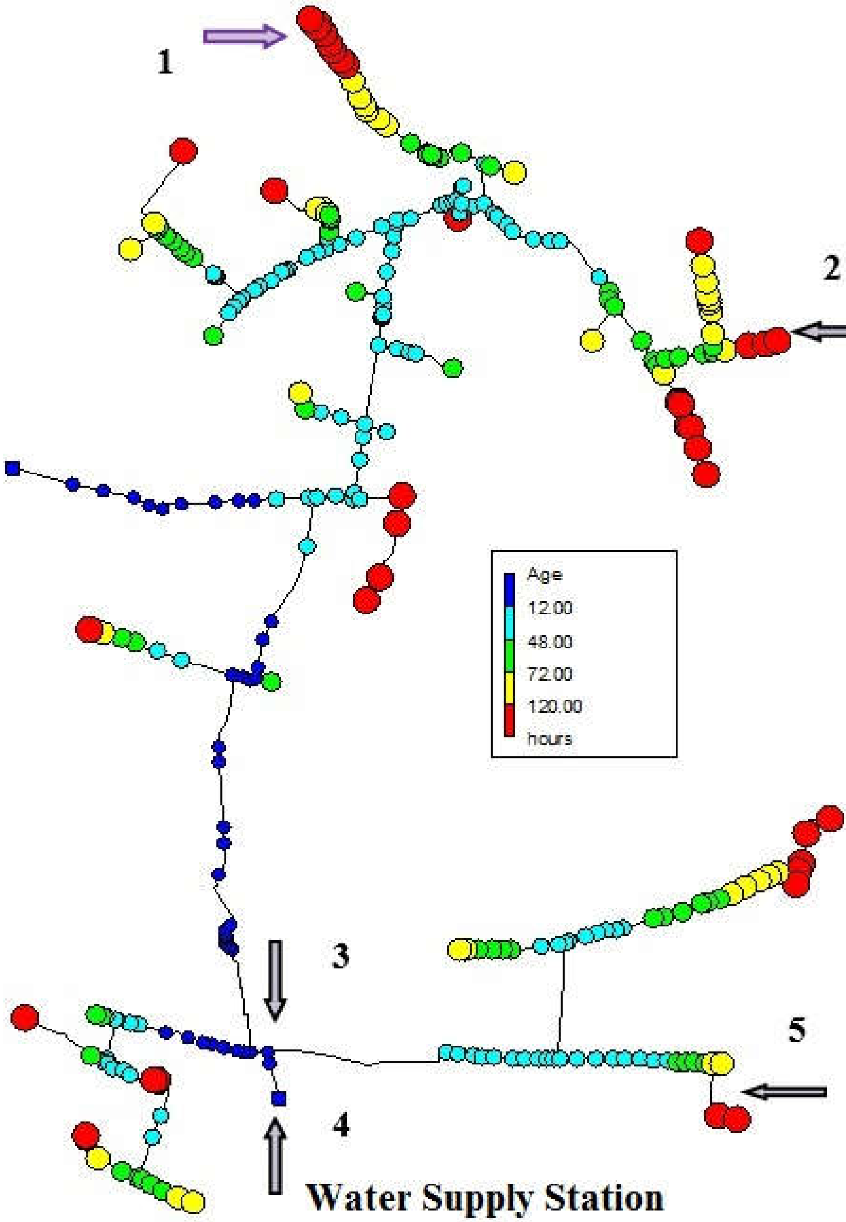

Fig. 1. The scheme of the water supply system with marked locations of water sampling (1–5)

Samples for microbiological analyses were extracted from measuring point 2 due to high water age at that point. The figure 2a presents an exemplary water sample, while on the figure 2b the iron bacteria on ferric-ammonium citrate medium are visible. Values of basic microbiological indicators are presented in table 2, where also values of source water indicators are presented. The analysis of source water parameters was pursued by water enterprise. Basing on results presented in table 2, it can be said that water from measuring point 2 does not fulfil the drinking water microbiological conditions (*Rozpodządzenie, 2010; Rozporządzenie, 2007*).

Table 2. Values of water quality parameters identified in water samples collected from the water supply network (29.01.2015)

Sample number, Water age [h]	1 *280*	2 *480*	3 *1*	5 *450*	4 – Water supply station	Water supply station 05-05-2014	Regulation value
pH	7.3	7.51	7.15	7.4	7.5	7.5	6–9.5
Conductivity [mS/cm]	4.5	4.34	4.15	4.28	4.24	<5	2.5
Alkalnity [mval/dm^3]	6.3	6.3	6.25	6.4	6.25	6.3	-
Hardness [mval/dm^3]	5.6	5.05	5.8	5.75	5.65	-	-
Cl^-	-	3.55	-	-	-	-	
Oxidability [mgO_2/dm^3]	4	4.4	5.2	5.2	5	-	5
N-NH_4						0.09	1.5
N-NO_3 [mg/dm^3]	1.3	0.9	1	1.2	1.2	1.5	1.5
Colour [mgPt/dm^3]	5	20	5	5	5	<5	15
Turbidity [NTU]	1.64	4.45	0.66	0.88	0.42	0.51	1
Dry matter [mg/dm^3]	349.4	352.5	318.1	289.7	333.6	-	-

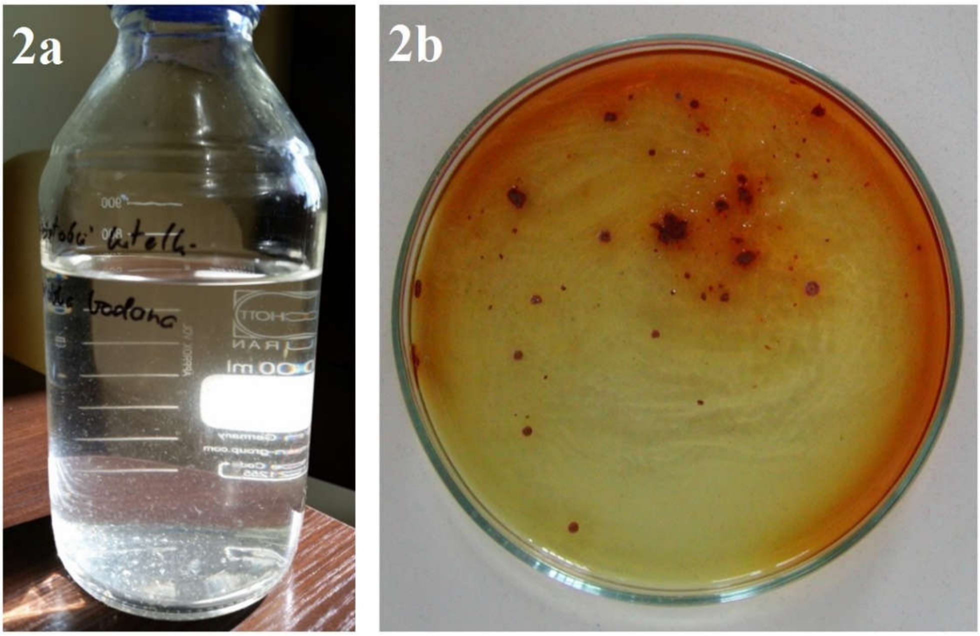

Fig. 2a) Water sample extracted from water supply network (measuring point 2)
Fig. 2b) Iron bacteria on ferric-ammonium citrate medium

Table 2. Results on bacteriological tests of water samples from measuring point 2 and water source

Indicator	Water form point 2	Source water	Regulation value
General microorganisms number in temperature 36±2^{o}C (mesophilic)	55 CFU/ml	Non detected	50
General microorganisms number in temperature 22±2^{o}C (psychrophilic)	$2{,}0 \cdot 10^3$ CFU/ml	Non detected	No improper changes
MPN of Fe(II)iron oxidizing bacteria	≥2400 CFU/100ml	No data	-
MPN of sulphate reducing bacteria	5 CFU/100ml	0 CFU/100ml	0

The Minister of Health Regulation (*Rozpodządzenie, 2010; Rozporządzenie, 2007*) classifies sulphate reducing bacteria as indicator organisms. According to valid criteria, in 100 ml of water from water supply network there should not be any cell of indicator bacteria. Endospores of anaerobic bacteria oxidizing sulphates (clostridia) occurs commonly in the environment. They can survive in water for a long time and are more resistant to physical and chemical actions (including chlorination) than vegetative forms. Therefore, they can testify time-distant or occasional contaminants. That group cause numerous food poisoning. The second important drinking water quality criterion is the general number of psychrophilic and mesophilic bacteria in 1 ml of water. In accordance to standards from previous Regulation of the Ministry of Health from 2007 (*Rozporządzenie, 2007*), the number of psychrophilic bacteria should not exceed 100 cells in 1 ml of water, while the number of mesophilic bacteria should not exceed 20 cells in 1 ml of water. However, the valid the Ministry of Health Regulation (*Rozpodządzenie, 2010*) does not define the number of permissible number of psychrophilic bacteria in water from water supply networks. Despite the fact, that it is commonly claimed that even the increased number of these bacteria do not threatens the human health [26], it should be noticed that the number of heterotrophic bacteria in water that exceeds 500–1000 CFU/ml can disturb the detection of E. Coli group bacteria. That disturbance refers to methods based on lactose fermentation including the method of membrane filtration and can have the negative influence on water consumers health (*EPA U.S., 1998*). Additionally, it should be underlined, that in water samples numerous iron bacteria oxidizing Fe(II) were detected. These bacteria cause the sedimentation of corrosion products on internal walls of pipes. On Figure 3b there is presented an exemplary fragment of a water pipe from examined water supply network. On internal pipe wall there is visible a white-rusty deposit. Microscope analysis revealed that the main component of a deposit is calcium carbonate, iron oxidise and iron hydroxides. Due to the fact, that the whole water supply network was built with PVC-U pipes, which were stabilize by lead compounds, the further water analyses were executed aimed for lead presence. Obtained results revealed that in all cases, registered values were below the detection device limit (10 μg/l). That limit is equal to permissible lead concentration in accordance to valid regulation (*Rozpodządzenie, 2010; Rozporządzenie, 2007*). Therefore, it seems that even the slight amount of sediment attached to internal surface of a water pipe (Fig. 3b) protects water from a lead eluviation.

Results of deposit analysis

The next stage of tests was an attempt to analyse the chemical composition of the deposit, which could be easily observed in the obtained samples. Fig. 3a shows a water sample extracted from measurement point 2, where the water age was the longest and water quality the lowest. The deposit was filtered off from water and mineralised. Low quantity of mineralised deposit (30 mg) means that the quantitative analysis results presented in Table 4 may be to a certain extent erroneous. Nevertheless, they do point out the presence of numerous elements in water, e.g. lead.

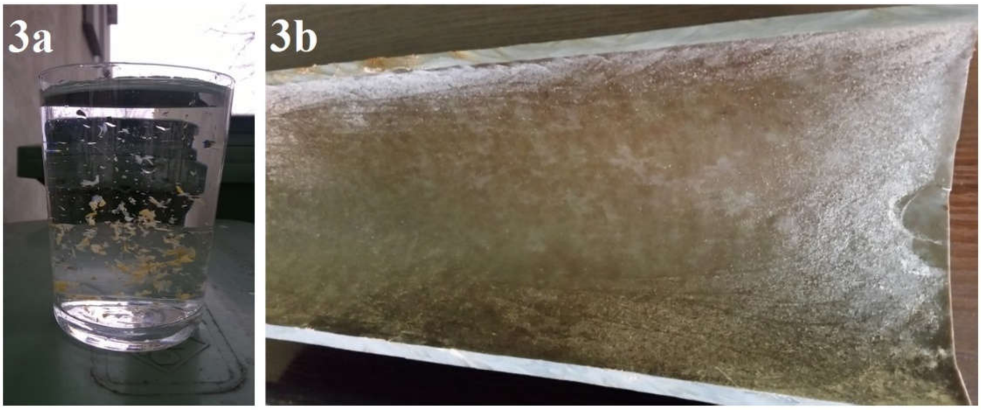

Fig. 3a) Water sample extracted from water supply network measuring point 2
Fig. 3b) Internal surface of PVC-U pipe (DN160, year of building: 1985) extracted from an existing water supply network

Table 4. Elements concentrations in deposit from water samples extracted from measuring point 2 of water supply network

Al	Ba	Ca	Co	Cu	Fe	K	Mg	Mn	Na	Ni	Zn	Pb
[%]	[mg]	[%]	[mg]	[mg]	[%]	[mg]	[%]	[%]	[mg]	[mg]	[%]	[%]
0.1	164	2.4	122	117	11.1	0.1	0.37	5.7	473	27	0.21	0.004

4 Summary and Conclusions

Among the analysed parameters of water from the supply network the highest change was observed at points of the longest water retention. At point 2 (water age 480 h) both colour, 20 mg Pt/dm^3, as well as turbidity, 4.45 NTU, significantly exceeded the limit values described in the Minister of Health regulation, which are 15 mg Pt/dm^3 and 1 NTU respectively.

Water samples extracted from measuring point 2 did not fulfil the drinking water microbiological conditions from the Minister of Health Regulation. The number of sulphate reducing bacteria (5 CFU/ml) and the general number of mesophilic bacteria (55 CFU/ml) were above the permissible limit.

Lead concentrations were below the test scale of the testing machine detection, as well as below 10 μg/dm^3, described in the Minister of Health regulation (*Rozpodządzenie, 2010; Rozporządzenie, 2007*).

Tests of suspended deposit confirmed the presence of numerous elements, inter alia, lead. Obtained numerical values can, however, be to an extent erroneous due to a very small mass of mineralised deposit.

References

1. Al-Malack M., Sheikheldin S. Y.: Effect of Solar Radiation on The Migration of Vinyl Chloride Monomer from Unplasticized PVC Pipes, Water Research, 2001, 35, 3283–3290.
2. Al-Malack M.H.: Migration of Lead from Unplasticized Polyvinyl Chloride Pipes. *Journal of Hazardous Materials*, B82, 263–274, 2001.
3. Benavides R., Edge M., Allen N.S., Mellor M., Harvey H., Schmets G.: The Evaluation Of An Innovative Costabiliser For Poly (Vinyl Chloride) – I. Inhibition of Discolouration and Stabilisation Performance in The Polymer. *Polymer Degradation and Stability*, 3, 311–318, 1996.
4. Cruickshank J.R.: Hydraulic Models Shed Light on Water Age. *Opflow*, 6, 18–21, 2010.
5. Edberg S.C., Allen M.J.: Virulence and risk from drinking water of heterotrophic plate count bacteria in human population groups. *Int. J. of Food Microbiol*., 92, 255–263, 2004..
6. EPA U.S.: Disinfectant and Disinfection By-Products Rule, 1998.
7. EPA U.S.: Effects on Water Age on Distribution System Water Quality, Washington D.C., 2002.
8. Fisch M., Bacaloglu R.: Mechanism of Poly (Vinyl Chloride) Stabilisation. *Plastics, Rubber and Composites*, 3, 119, 1999.
9. Gato-Trinidad S., Jayasuriva N., Roberts P.: Understanding urban residential end uses of water. *Water Science & Technology*, 64/1, 36–42, 2011.
10. Hem L.J., Efraimsen H.: Assimilable organic carbon in molecular weight fractions of natural organic matter. *Water Research*, 4, 1106–1110, 2001.
11. Kowalska B., Kowalski D., Kwietniewski M.: Organotin Compounds Leached from PVC Pipes in Water Distribution Systems. *Instal*, 4, 42–46, 2009.
12. Kowalski D., Kwietniewski M., Musz A., Widomski M.: Charakterystyka wybranych metod płukania i czyszczenia przewodów wodociągowych. *Ochrona Środowiska*, 1, 27–30, 2008.
13. Kulbik M.: Komputerowa symulacja i badania terenowe miejskich systemów wodociągowych. Politechnika Gdańska, Monografie vol. 49, 2004.
14. Kuś K., Gamrot B., Malicka K., Ścieranka G.: Wpływ eksploatacji i stanu technicznego sieci na jakość wody wodociągowej. *Ochrona Środowiska*, 3, 17–20, 2001
15. Kuś K., Grajper P., Ścieranka G., Wyczarska-Kokot J., Zakrzewska A.: Wpływ spadku zużycia wody w miastach zaopatrywanych przez wodociąg grupowy GPW w Katowicach na jakość wody w systemie dystrybucji. *Ochrona Środowiska*, 3, 29–34, 2003.

16. Lasheen M.R., Sharaby C.M., El-Kholy N.G., Elsherif I.Y., El-Wakeel S.T.: Factors Influencing Lead And Iron Release From Some Egyptian Drinking Waterpipes. *Journal of Hazardous Materials*, 160, 675–680, 2008.
17. LeChevallier M.W.: The case for maintaining a disinfectant residual. *Journal American Water Works Association*, 1, 86–94, 1999.
18. Lethola M.J., Miettinen I.T., Vartiainen T. Myllykangas T., Martikainen P.J.: Pipeline materials modify the effectiveness of disinfectants in drinking water distribution system. *Water Research*, 10, 1962–1971, 2005.
19. Rozporządzenie Ministra Zdrowia z dnia 20 kwietnia 2010 r. zmieniające rozporządzenie w sprawie jakości wody przeznaczonej do spożycia przez ludzi (Dz.U. 2010 nr 72 poz. 466).
20. Rozporządzenie Ministra Zdrowia z dnia 29 marca 2007 r. w sprawie jakości wody przeznaczonej do spożycia przez ludzi (Dz.U. nr 61 poz. 417).
21. Sadiki A-I., Williams D. T., Carrier R., Thomas B.: Pilot Study of the Contamination of Drinking Water by Organotin Compounds from PVC Materials. *Chemosphere*, 32, 2389–2398, 1996.
22. Simard A., Pelletier G., Rodriguez M.: Water residence time in a distribution system and its impact on disinfectant residuals and trihalomethanes. *Journal of Water Supply: Research and Technology – AQUA*, 6, 275–389, 2011.
23. Sokołowska A., Oleńczuk-Neyman K.: Badania zmian jakości mikrobiologicznej wody w sieci wodociągowej aglomeracji trójmiejskiej. *Ochrona Środowiska,* 4, 15–19, 2009.
24. Świderska-Bróż M.: Czynniki współdecydujące o potencjale powstawania i rozwoju biofilmu w systemach dystrybucji wody. *Ochrona Środowiska*, 3, 7–13, 2010.
25. Traczewska T.M., Sitarska M.: Materiały syntetyczne podłożem dla rozwoju biofilmu w systemach dystrybucji wody. *Ekotoksykologia w ochronie środowiska: praca zbiorowa pod red. B. Kołwzan i K. Grabasa*. Wrocław: Polskie Zrzeszenie Inżynierów i Techników Sanitarnych. Oddział Dolnośląski, 443–450, 2008.
26. Volk C.J., LeChevallier M.W.: Impacts of the reduction of nutrient levels on bacterial water quality in distribution systems. *Applied and Environmental Microbiology*, 11, 4957–66, 1999.

Practical stabilization methods of groundwater in north-western region of Ukraine

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Abstract

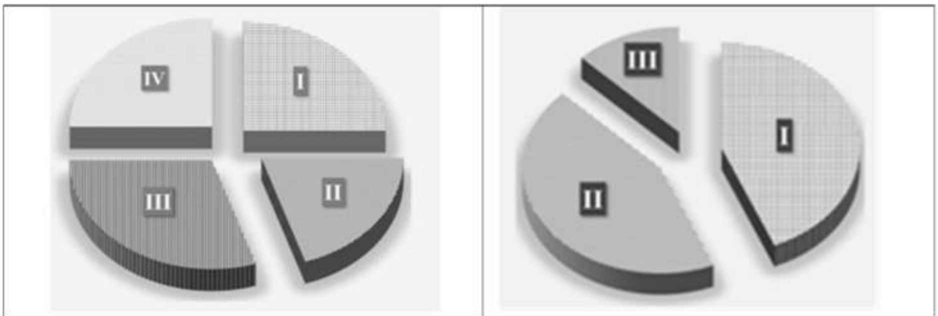
The aim of this work is to choose the optimal method of stabilizing treatment for aggressive groundwater that contains iron compounds. The studies were conducted under production conditions on underground waters, which had different acidity, alkalinity, and organic compounds. The influence of physicochemical and microbiological parameters of water quality, which change depending on time of water retention in a supply network, on water stability were examined. The studies took into account physicochemical parameters such as: Fe, alkalinity, permanganate value, salt and Ca^{2+} ions content as well microbiological parameters: iron bacteria *Gallionella*, and *Crenothrix*. The changes were studied of saturation indexes (I_L, I_R), depending on the time spent in water network. The optimal dose of the reagent for stabilizing water in distribution systems was determined depending of various of water quality parameters. The pattern was observed concerning in the quality of water depending on the length of the surveyed points relative to iron removal station location. The interrelation between the reduction and oxidation reduction potential and the increased concentration of iron and permanganate oxidation was revealed. The technology and equipment for stabilizing treatment station was developed.

Keywords

iron bacteria, types of corrosion, aggressive groundwater, stabilizing treatment technology, Rizner and Langelier saturation indexes

1 Introduction

The research on the qualitative composition of artesian water at the existing water intakes of Ukraine states the fact of the emergence of progressive deterioration trend for such key parameters as: iron, hardness, total mineralization, microbiological indicators - which are indirect indicators for increasing its aggression concerning metal and concrete (*Kvartenko and Safonov, 2015; Kvartenko, 2011*). Pipe wall thickness is reduced over time as a result of active corrosion that leads to accidents. Our monitoring of groundwater aggressiveness degree in over 80 localities in Volyn, Rivne, Zhytomyr, Khmelnytsky, Lviv regions of Ukraine found that water supply in nearly 60% of them is based on using underground waters with different degrees of aggressiveness towards concrete and metal (13% showing ability to carbonate deposits on piped walls, 27% relates to stable water). The greatest degrees of aggressiveness with underground water horizons are northern districts of Volyn and Rivne which are presented in Fig. 1.



A) North of Rivne region I – mild corrosion (25%); II – tendency to corrosion (20%); III – very high degree of corrosion (30%); IV – an extremely high degree of corrosion (25%)	B) Volyn region I – mild corrosion (43,75%); II – tendency to corrosion (43,75%); III – very high degree of corrosion (12,5%);

Fig. 1. The diagram of groundwater corrosive action

Reasons are determined for increased degree of aggressiveness of groundwater in the region in the period from 2000 to 2014: the decrease in acidity, alkalinity and reduced concentration of Ca^{2+} ions. The existing iron removal plants commissioned in 60s–70s of the twentieth century, based on simplified technology or deep aeration followed by filtration - cannot solve this problem. To address the question of initial water purification with further maintenance of its quality during transportation, one must use comprehensive clean groundwater with their subsequent stabilizing treatment. Great contribution to the development of technologies of stabilizing treatment was made by (*Langelier, 1936; Larson, 1942; Stiff, Jr., et. al., 1952; Van Waters et. al., 1964; Klyachko et. al., 1971; Stumm,* *1981; Wojtowicz, 1995; Alekseev 2006; Makarenko, et. al., 2012)*. After analyzing the works of these authors we can conclude that the main stabilizing treatment methods are divided into:

Chemicals:

- reagent methods using lime, soda, sodium hydroxide;
- reagent method using hydrochloric and sulfuric acid;
- reagent method using inhibitors based on phosphoric acid salts;
- using of complexones.

Filtration:

- filtration using marble chips, magnomasses;
- filtration using slightly acid cations.

Physical:

- magnetic treatment;
- radiowave treatment;
- aeration stabilization.

Chemical treatment methods are based on the insertion of minor doses of reagents into water settler, that bind hardness salts and prevent them from precipitated on the surface of pipelines; form a protective anti-corrosion film on the surface of pipelines. Systems for domestic water supply used liming, dispensing soda, sodium hydroxide (*Stiff and Davis, 1952; Klyachko, 1971; Wojtowicz, 1995*).

2 Materials and Methods of Research

Research was carried out by standard methods using devices: photoelectric KFK-3, ionomers universal Ev-74, microscope "Byomed" x 640 on the lens.

To study the dynamic changes of water quality and its aggressiveness in characteristic points of water supply systems the following parameters were investigated:

1. Permanganate oxidation which is characterizing the presence in water of easily oxidative organic compounds and the level of water biogenic.
2. Iron compounds – the changes of which characterize in water network passing corrosion processes.
3. pH - which characterizes the acidity of water.
4. The content of Ca^{2+}, total salt content, water alkalinity, temperature - parameters which determine the stability indexes of water.

Microbiological indicators for iron bacteria, thio bacteria, iron reducing bacteria in water content - whose presence characterizes the ability of the water for the biological corrosion.

The stability of the water is determined by the following formulas (*Klyachko, 1971*):

$$pH_s = f_1(t) \quad f_2(Ca^{2+}) \quad f_3(Alk)+f_4(P) \tag{1}$$

where: $f_1(t)$ – water temperature function as values of thermodynamic constants depend on temperature, $f_2(Ca^{2+})$ – function of calcium concentration in water, $f_3(Alk)$ – function of total alkalinity in water, $f_4(P) = 2.5\sqrt{\mu}$ – function of total salt content in water, μ – ionic strength of solution.

Using the calculation formula (1) is achieved by using the calculated schedule (*Klyachko*, 1971). According to this method, based on chemical analysis of water data is the calculation of the pH value, which corresponds to the equilibrium state in the solution of carbonic compounds. This value is called "the equilibrium pH of the water saturated with calcium carbonate" and denoted pH_S.

Langelier index of the saturation:

$$I_L = pH_0 + pH_s \tag{2}$$

Value – of the $f_1(t)$, $f_2(Ca^{2+})$, $f_3(Alk)$, $f_4(P)$, determined by the initial data for Langelier and Hoover charts. The pH_0 – pH is a source of water.

Rizner indexes:

$$I_L = 2 \quad pH_s + pH_0 \tag{3}$$

Estimated values of these parameters for intake sites are shown in Tab. 1.

Table 1. Parameters of quality and stability indices of groundwater

The name of the water intake	"Pivdenny" Novovolynsk town	Berezne town	Rokitne town
pH_0	6.75–7.1	7.3	6.0
Alkalinity [ekv-mg/dm^3]	6.2	2.4–2.85	0.8
CO_2 ^{aggr} [mg/dm^3]	20–24	30	80
H_2S [mg/dm^3]	1.5–1.8	Less than 1.0	1.7–4.0
Total salt content [mg/dm^3]	665	235	228
Ca^{2+} [mg/dm^3]	124	96	38
$Fe_{overall}$ [mg/dm^3]	Less than 1.6	0.9–2.45	Less than 30
I_L	– 0.32	– 0.48	– 2.4
I_R	7.64	8.28	10.8

Doses of reagents to stabilize water are determined by the formula:

$$D_L = e \;\; \beta_L \;\; A \;\; 100/P \tag{4}$$

where: D_L – dose of lime [mg CaO/dm^3], β_L – coefficient determined by nomograms (*Klyachko, 1971*), A – alkalinity of water before the stabilizing treatment [ekv-mg/dm^3]; e – the equivalent weight of alkali, for $Ca(OH)_2$ – 28 [mg/mEq] (in terms of CaO); P – active substance content in the technical product [%].

The concentration is determined of Ca^{2+} ions in 2% solution of lime.

We **s**elect the volume V = 100 [ml], settled on top of the recycling tanks 2% solution of lime, and by the technique (*Semenov, 1977*) determine the content of Ca^{2+}. Then we make recalculation for CaO [mg /-dm^3]:

$$C_{CaO} = 1.4 \;\; C_{Ca}^{2+} \tag{5}$$

By calculated reagent dose (D_L) and C_{CaO} value the volume is determined of clarified solution per 1000 [ml] of source water:

$$V_{sol} = \frac{D_L \, 1000}{C_{CaO}} \tag{6}$$

where: D_L – dose of lime [mg CaO/dm^3] in CaO, C_{CaO} – concentration of CaO [mg/dm^3].

The conversion factor is determined:

$$K = \frac{1000}{V_{sol}} \tag{7}$$

Consumption of the working solution of metering pumps:

$$Q_{pump} = \frac{Q_{station}}{K} \tag{8}$$

where: $Q_{station}$ – hour water flow of iron removal station [m^3/h].

3 *Results and Discussion*

We analyzed the state of the water supply in towns of Novovolynsk, Vladimir-Volynsk and Berezne. The aim of our researches was to determine the water quality parameters (change of Ca^{2+} ion concentration, $Fe_{overall.}$, values pH, redox potential and permanganate oxidation) at various points of pressure water lines and water supply systems (*Kvartenko,2013*). We studied changes of indexes of water stability. The increase of concentration of iron compounds and decrease in the value of the redox potential was found in the dead-end of water main points in a water supply system - see Fig. 2. The results of the analysis of the corrosive pollution indicated the presence of sulfate and iron reducing bacteria that restore environment causing biological corrosion process – see Fig. 3.

The activity of iron bacteria, according to experts, may cause from 50 to 80% of pipeline corrosion damage to water supply system. Microbiological corrosion can be done in different ways:

– by direct influence of metabolic products of microorganisms (CO_2, H_2S, NH_3, organic and inorganic acids) on metallic and nonmetallic structures;
– through formation of organic products that act as catalysts or corrosive reactions polarizers;
– when corrosive reactions are a separate part of the metabolic cycle of bacteria.

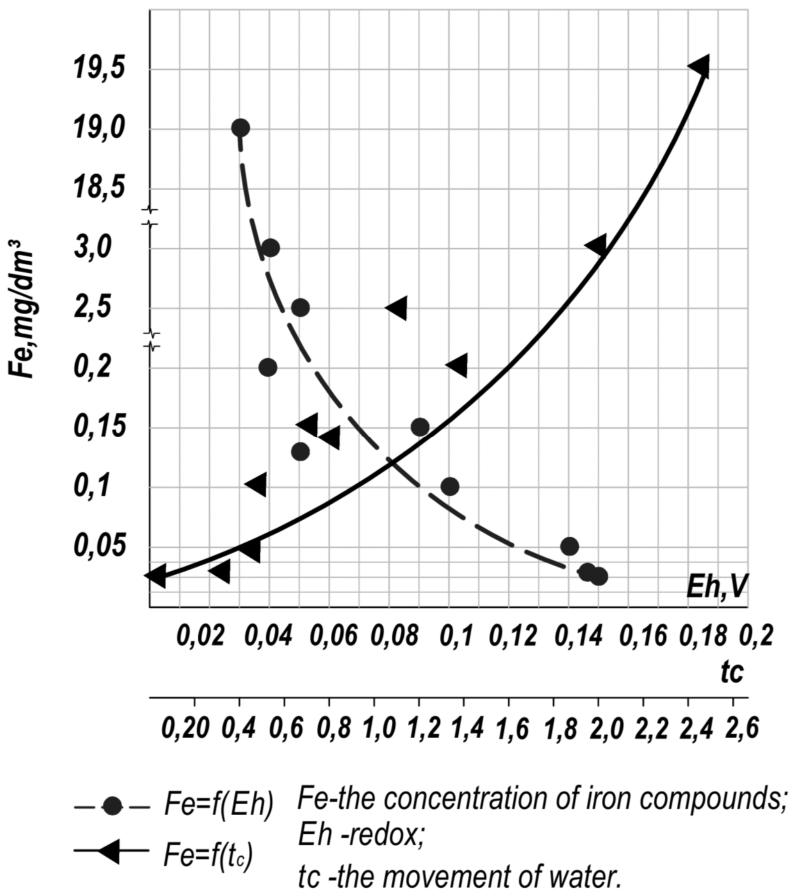


Fig. 2. The Graph of iron concentration values of the redox potential: 1 – Fe= $f(Eh)$ and the contact time of water in the pipeline; 2 – $Fe_{ov.}=f(t_{cont})$

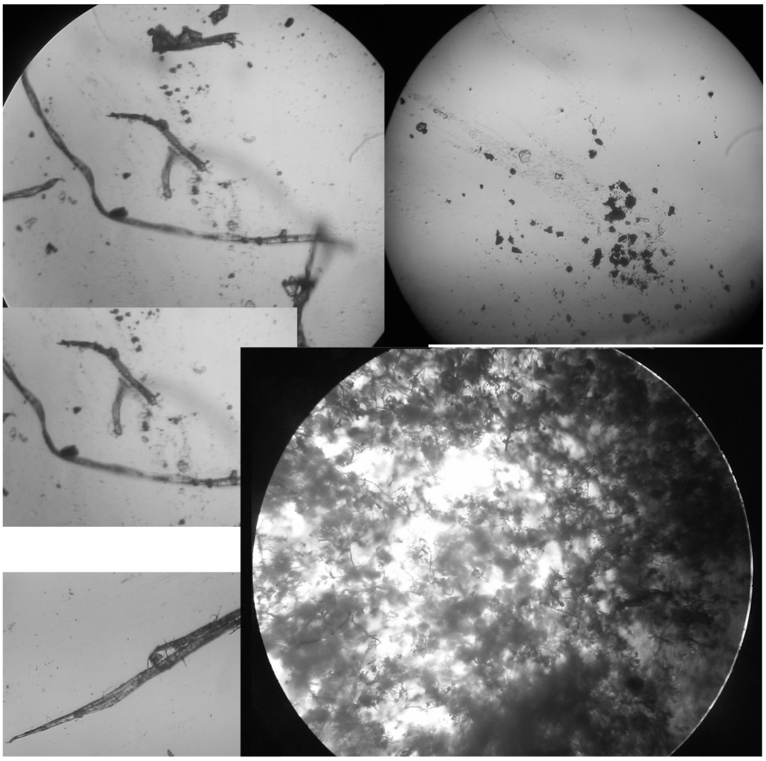


Fig. 3. Sedimentation and bacterial growth on the inner wall of the pipes (iron bacterial *Gallionella*; iron reducing bacteria)

Processes of corrosion, which occur on the surface of materials, depended on the physical and chemical conditions in the surface layer. The intensity of corrosion depends on pH, oxygen concentration, redox potential and the concentration of chemical compounds. There are aerobic and anaerobic types of corrosion.

Aerobic type of corrosion is carried out in the presence of a sufficient number of free or dissolved oxygen. Aerobic corrosion exposes concrete and steel water pipes, pumps and various equipment of water supply. Aerobic pathogens are corrosion thio, nitrite and iron bacteria. As a result of life activity of thio and nitrifying bacteria an aggressive corrosive environment is created by the accumulation of sulfuric and nitric acids - end products of their metabolism.

Anaerobic type of corrosion. The main causative agents of anaerobic corrosion are sulfate-reducing bacteria responsible for the restoration of sulphate to hydrogen sulfide belonging to the genus of *Desulfovibrio* and *Desulfotomaculum* bacteria. Currently, there are several hypotheses on the mechanism of anaerobic corrosion of steel, iron and aluminum under the influence of sulfate-reducing bacteria, of which the following are of interest:

- cathodic depolarization is manifested in the stimulation of cathode areas metal by bacteria moving and consuming polarized hydrogen;
- cathodic depolarization stimulation solid iron sulfide formed by the interaction of iron ions from the sulfide ions which is the end product of bacterial recovery of sulfates.

Also there is small increase in the quantity of permanganate oxidation in the test points within 1.6 to 3.3 mg O/dm^3. At the Fig. 4 presents the permanganate oxidation increase range is in accordance with the location of sampling points.

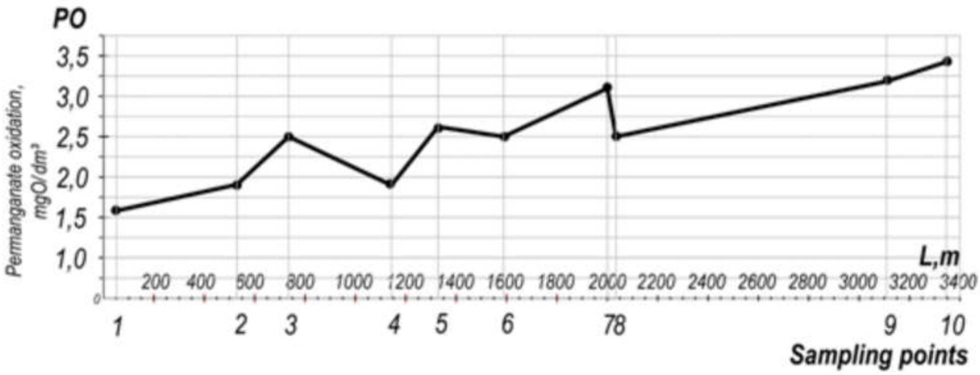


Fig. 4. Graph of changing permanganate oxidation, depending on the distances to the sampling points

The reused water pollution by corrosion products leads to the deterioration of its quality - namely, increases turbidity, color, appearance of unpleasant tastes and odors, iron hydroxide. Therefore, along with iron removal from water, it is necessary to carry out their stabilization processing. To determine the region of the outlets surveyed corrosive activity zones, their values are plotted on a Pourbaix diagram in the system Fe^{2+} - H_2O. All points are in region of the corrosive action of water, and as the distance increased from the iron removal plant, the tendency of increased water levels of aggressiveness by Langelier (from – 0,26 to – 0,51) and Rizner (from 7,85 to 8,12) indexes was observed. Thus, with increasing length of stay in the water network water increases its aggressive properties – see Fig. 5.

As a result of the field research on Novovolynsk and Berezne groundwaters we identified the optimal dose of alkaline reagents, changes depending on pH, alkalinity water, Ca^{2+}, index stability by Langelier and Rizner depending on the time of the stabilized water in water supply systems, with different doses of lime solution, and the optimal concentration of Ca^{2+} in the working solution pumps costs based on the hourly consumption of water in the settlements. After our research it was possible to recommend the implementation of the following technological scheme of water treatment: aerators-degassers, iron removal station, power stabilization treatment unit.

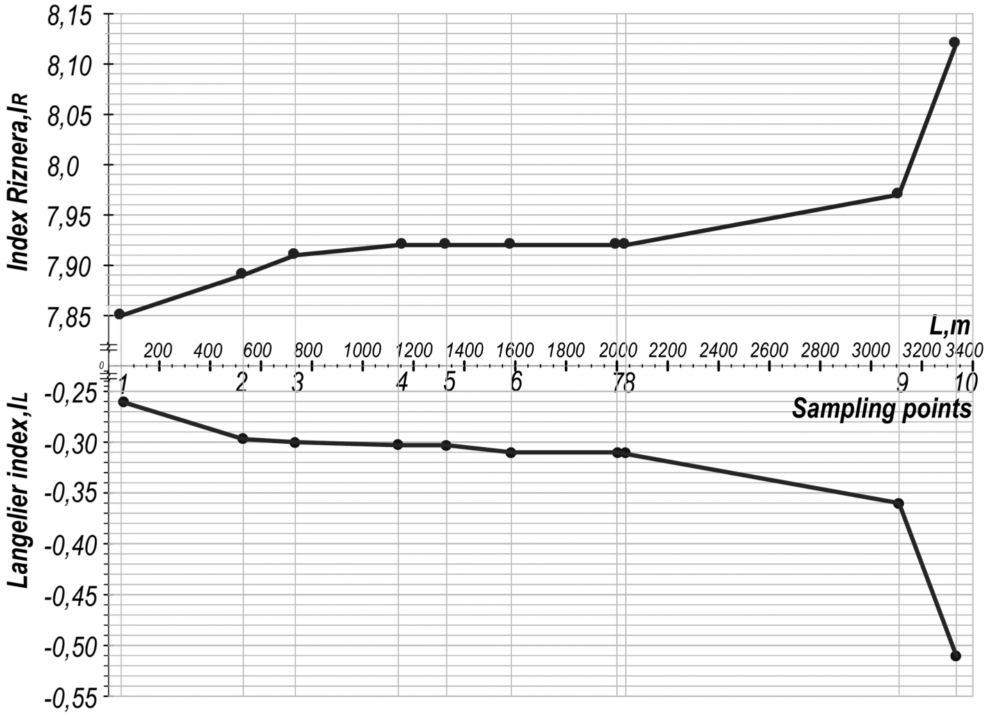


Fig. 5. Graph of changes of indexes stability by *Langelier* (1) and *Rizner* (2) distance from the location of sampling points

Stabilizing treatment unit consists of solvent tanks and recycling equipped tanks - with thin-layer settling tanks for partial clarification of the working solution, groups of pumps both for hydraulics mixing dosing partial clarified working solution to the network. At the heart of the stabilizing treatment technology is the foundation principle of gradual formation of the protective carbonate film on the inner surfaces of pressure water lines and on distribution network by introducing alkaline reagent - clarified solution of estimated lime concentration. This principle also includes the research of expenses depending on the quality of source water, graphs of water concentration and feeding pumps of the second recovery followed by maintaining the stability of the water by the lower doses of reagent. In the process of stabilizing treatment it is necessary to control the formation of protective carbonate film on the pipe walls. For this purpose, it is desirable to allocate different parts in water network areas that can be disabled for review. In addition, it is advisable to monitor the change of head loss on control pipelines. Bench tests have shown that, at first, formation of carbonate film pressure loss in pipes is slightly reduced by decreasing their absolute roughness, and with further build-up of calcium carbonate layer begins to grow. With the proper implementation of stabilizing treatment process optimum hydraulic properties of pipes should be kept.

The growth of carbonate film can be uneven along the length of pipes. In the nearest to the point of discharge pressure processing sites and distribution network carbonate film can go thicker than in remote areas. The alignment of the thickness of carbonate film can contribute to the alternating water alkalizing.

As can be seen from the graph Fig. 6 *Langelier* index of initial water ranges from –0.658 to –0.58 for cycle of filtration. With $I_L < 0$ – this water is aggressive and refers to mild corrosion degree. The *Rizner* index for source water varies between 8,3…8,47 – that water tends to create corrosion.

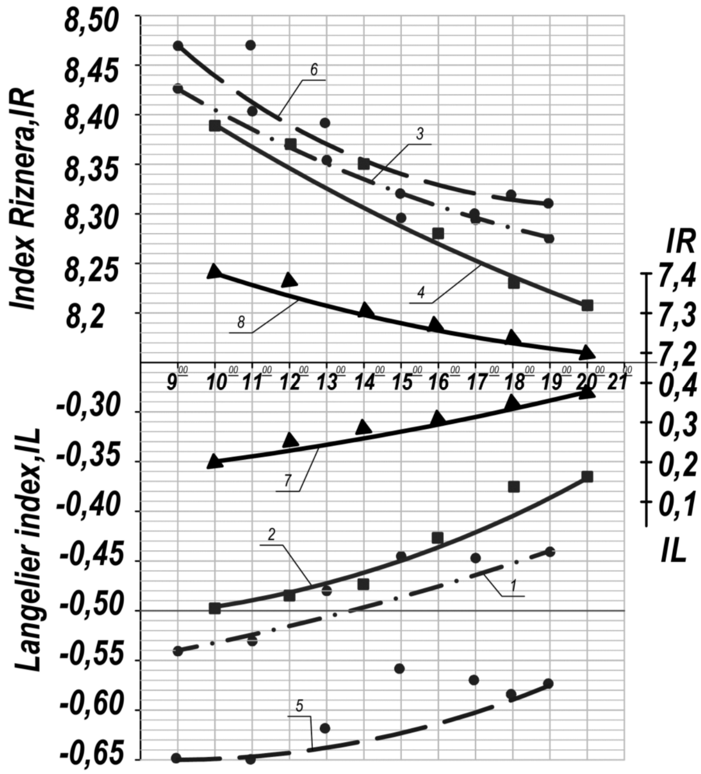


Fig. 6. Schedule changes in the values of indices of stability during cycle of filtration. *Langelier* index values after: 1 – bioreactor, 2 – filters, 5 – source of underground water, 8 – stabilization treatment. *Rizner* index values after: 3 – bioreactor, 4 – filters, 6 – source of underground water, 7 – stabilization treatment

After the bioreactor *Langelier* index is slightly increased, but ranges from –0,43...–0,539. This water is also aggressive. *Rizner* index decreases and is 8,43 ... 8,28 – but this water still tends to create corrosion. After the filter *Langelier* index during the cycle of filtration is: –0.495 …–0,365. That water is also aggressive and prone to create corrosion. It was only after the stabilization processing unit acquires the filtrate quality is not aggressive.

The proposed technology of stabilizing treatment is introduced as a stabilizing treatment unit in the water supply intake of Novovolynsk "Pivdenny", in working designs of iron removal plants in towns of Koretz, Berezne, Rokitne settlement, in schools of villages Balashivka and Stare Selo of Rivne region. Figure 7 shows a block diagram of process modules of stabilizing treatment intake site "Pivdenny".

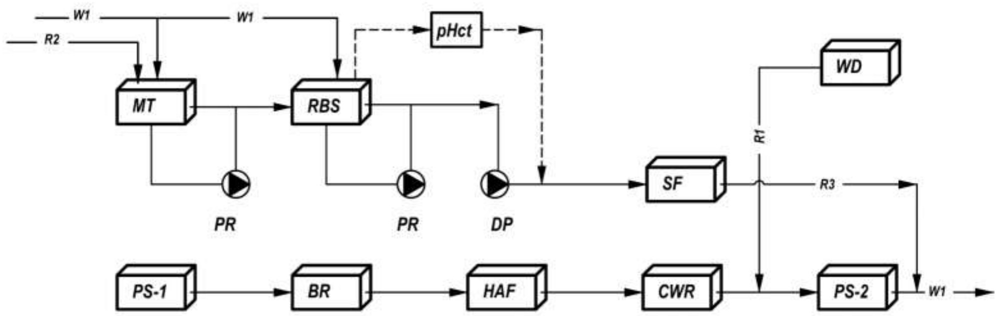


Fig. 7. The block of technological module stabilizing treatment unit in catchment area "Pivdenny": *BR* – bioreactor, *HAF* – quick filter with automatic hydraulic system flushing, *MT* – recycling tanks of hydro mixers concentrated solution, *RBS* – Clarifiers – recyclers of working solution with thin–settlers, *PR* – circulating pumps, *DP* – dosing pumps, *pHct* – *pH* controllers of working solution

Water treatment stabilization station in the town of Novovolynsk is shown in Fig. 8.

Table 2 shows the dependence of doses of lime dosing pumps on the performance parameters of water quality. The calculations are made for alkalinity [ekv-mg /dm^3] and content of Ca^{2+} in the source water of 100 [mg/dm^3].

This table represents the results of studies showing changes in the I_L depending on the expenses quanhty of pumping station water supply intake "Pivdenny", dose of lime and consumption of the working solution of metering pumps. In the numerator (columns 8, 9) shows the flow of solution illuminated mortar when the concentration of calcium ions in the upper part of the clarifiers - recyclers 1200 mg/dm^3, and the denominator under 900 mg/dm^3.

Recycling tanks of hydro mixers

Clarifiers - recyclers of working solution

Dosing pumps with pH controllers of working solution

Block thin-layer tank in lighter - recycling

Fig. 8. Water treatment stabilization station of the town Novovolynsk

Table 2. The dependence of doses of lime dosing pumps on performance parameters of water quality: I_L – *Langelier* index of the saturation [-], D_L – dose of lime [mg CaO/dm^3], β – coefficient [-] determined by nomograms (Klyachko, 1971), $Q_{station}$ – hour water flow of iron removal station[m^3/h], Q_{pump} – consumption of the working solution of metering pumps [m^3/h]

I_L	pH$_o$	β	D_Lx1.2	D_Lx2	$Q_{station}$	Q_{pump}x1.2	Q_{pump}x2
			[mg CaO/dm^3]		[m^3/h]		
1	**2**	**3**	**4**	**5**	**7**	**8**	**9**
–0.1	7.20	0.020	4.7	8.0	220	0.6/0.9	1.06/1.5
–0.25	7.10	0.055	13.0	21.6	220	1.7/2.5	2.8/4.2
–0.30	7.00	0.080	19.0	31.0	220	2.5/3.7	4.1/6.0
–0.35	7.00	0.090	21.0	35.0	220	2.75/4.0	4.6/7.0
–0.40	6.99	0.120	28.0	47.0	220	3.7/5.5	6.0/9.0
–0.45	7.00	0.130	31.0	51.0	220	4.0/6.0	6.7/10
–0.5	7.00	0.140	38.0	63.0	220	5.0/7.6	8.0/12

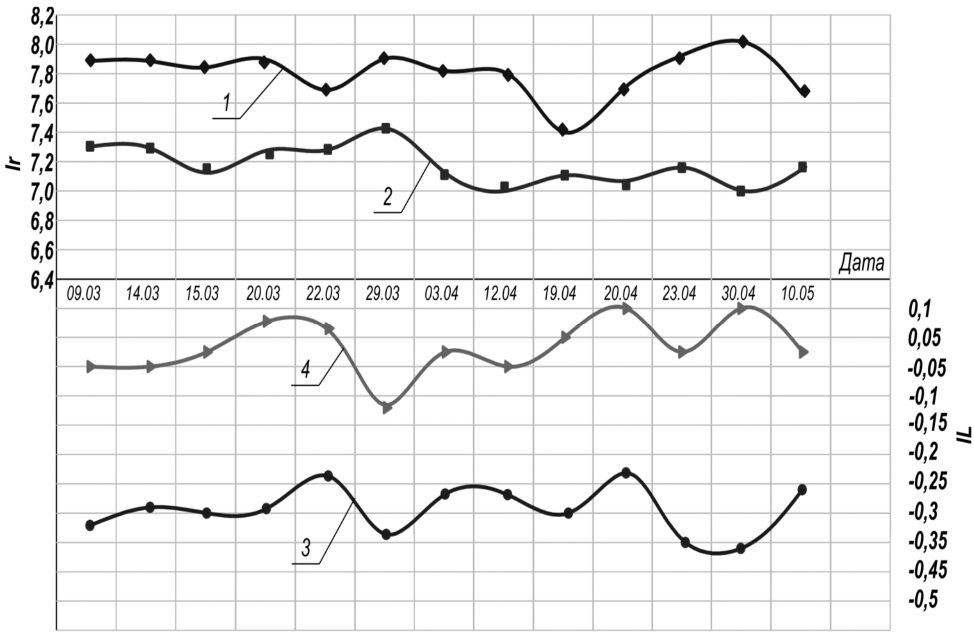


Fig. 9. The results of studies on the stability of water changes during 09.03.07 to 10.05.07 in intake "Pivdenny". Change of the value of *Rizner* index: 1– inlet water, 2 – outlet water. Change of the value of *Langelier* index: 3 – inlet water, 4 – outlet water

As can be seen from the graph in Fig. 9 while administering clarified the solution process of stabilizing treatment take place.

4 Conclusions

As a result of research we found no deterioration in the quality of stabilized water that delivers to consumers, depending on time of stay in the water supply networks, especially in the dead-end sections of the water supply network. The interrelation is shown between decreases in redox potential, increased concentrations of iron and permanganate oxidation. The optimal doses of the reagent are found for stabilizing treatment, depending on performance quality. The technology and equipment unit are developed for stabilizing treatment that allows to correct alkalinity reagent supply based on changes in network costs and parameters pH of Ca^{2+} in the clarifier - recyclers.

References

1. Langelier W. F.: The analytical control of anticorrosion water treatment. *Journal of American Water Works Association*, 28, 1500–1521, 1936.
2. Larson T. E., Buswell A. M.: Calcium carbonate saturation index and alkalinity interpretations. *Journal of the American Water Works Association*, 34, 1667–1684, 1942.
3. Stiff Jr. H. A., Davis L.E.: A method for predicting the tendency of oil field water to deposit calcium carbonate, *Journal of Petroleum Technology*, 4 (09), 213–216, 1952.
4. Stumm W. , Morgan J. J.: Aquatic Chemistry. New York, John Wiley & Sons 1981.
5. Van Waters & Rogers: Technical Information Bulletin FK 41464. Scale Formation and pH Control in Swimming Pools. 1964.
6. Wojtowicz J. A.: Swimming Pool Water Balance – Part 1: Effect of Cyanuric Acid and Other Interferences on Carbonate Alkalinity Measurement. *Journal of the Swimming Pool and Spa Industry*, 1, 6–12, 1995.
7. Алексеев Л. С.: Совершенствование методов стабилизационной водообработки для регламентирования качества и расхода воды в агропромышленном комплексе. Дисс. д-ра технических наук. М.: 2006.
8. Квартенко А. Н.: Характеристика подземных вод Северо-Западных областей Украины и технологические схемы их кондиционирования. *Проблеми водопостачання, водовідведення та гідравліки. Науково-технічний збірник*, Випуск 16, 32–40, КНУБА 2011.
9. Квартенко А. Н.: Технология кондиционирования агрессивных подземных вод с низким щелочным резервом, содержащих аммиак и железоорганические комплексы. *Вісник Донбаської національної академії будівництва та архітектури. Збірник наукових праць*, Випуск 5 (103), 52–60, Макіївка 2013.
10. Квартенко О. М., Сафонов Р. В.: Аналіз ступеня агресивності підземних вод Рівненської області. *Вісник НУВГП. Збірник наукових праць*. Випуск1(69), 58–66, Технічні науки. - Рівне 2015.
11. Клячко В. А., Апельцин И. Э.: Очистка природных вод. Издательство по строительству, 1971.
12. Макаренко І. М., Глушко О. В., Рисухін В. В., Малін В. П.: Застосування слабкого катіоніту DOWEX MAC-3 для стабілізаційної обробки води. *Восточно-Европейский журнал передових технологий*, з/6 (57), 16–20, 2012.
13. Семенов А. Д.: Руководство по химическому анализу поверхносных вод суши". Гидрометеоиздат, Ленинград 1977.

Wastewater management system of the brewing industry

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Abstract

In order to reduce the influence of wastewater from enterprises on the environment extreme relevance is gained by improvement of the monitoring system at each stage of technological process. A new tool – calculation of the polluting substances concentration is suggested to be entered into the monitoring system on the basis of determination of material balance of technological process of production that will allow prediction of qualitative and quantitative composition of sewage for the selected period. The system can be used in any enterprise, but the example with all calculations is given for the Mykolaiv Branch of "SUN InBev Ukraine" which became the object of research. The scope of the study covered the process of wastewater formation of the enterprise. Realization of tasks demanded the use of general scientific methods: analysis, synthesis, systematization and generalization in the course of studying of the corresponding literature on the research subject; modeling, formalization, comparison - at drawing up the calculation scheme of concentration of the polluting substances in sewage; supervision - during studying the technological scheme of production; and also methods of mathematical data processing in MS Excel.

Keywords
wastewater, pollutants, material balance, control, management, food industry

1 Introduction

Today sewage from plants is the main source of pollution of superficial water objects. The issue of environmental security enterprises of food industry, namely the aspects of qualitative composition of effluents, are presented in publications (*Kolotylo et al., 2003; Kunze, 2001; Muravyov, 2004; Kovalevskaya, 1993; Lebedevych, 2008, Rockstrom et al., 2009*). Now control of sewage has only the statistical attribute. Therefore extreme relevance is gained by improvement of the monitoring system behind sewage at each stage of the technological process taking into the rules of acceptance of wastewater and surface water objects according rules and standards (1 4; 11 15). The system consists in drawing up a material balance of the technological process, definition of the main polluting substances on the basis of what calculation of masses and concentration of the substances in sewage is made for a certain period. A similar system allows seeing a full picture of impact of the enterprise on the environment, in particular on the water resources, to know, what impact each process has on the enterprise in the general sewage pollution. The system helps to determine the concentration of those substances in wastewater which is not defined with the use of laboratory measures. Though, complete to replacement of the laboratory control over sewage is not the purpose of the offered system, it can add its results, because single tests on wastewater are not always indicative.

- The objective of the research is modernization of the wastewater control system on the basis of calculation of substances' mass balance.
- In order to meet the objective there is a need to solve the following problems:
- analysis of the technological process of the enterprise, drawing up scheme of sewage formation;
- calculation of concentration of the polluting substances in sewage of the plant for a certain period;
- development of recommendations on optimization of the wastewater control system.

The offered system can be used at any food industry enterprise, but the example with all calculations is provided for the Mykolaiv Branch of "SUN InBev Ukraine" which became the object of research. The formation process of wastewater of the enterprise has been selected as the scope of research.

General scientific methods are applied in order to execute the tasks such as analysis, synthesis, systematization and generalization; modeling, formalization, comparison drawing up the scheme of calculation of the polluting substances concentration in sewage; supervision during studying the technological scheme of production and also methods of mathematical data processing in MS Excel.

2 *Research part*

The modern wastewater control system in Ukraine consists in periodic sampling, carrying out the laboratory analysis of their structure and informing the enterprise on the conducted research (Fig. 1). However, the prospect of achieving sustainable development is possible when not only a simple measurement of sewage composition is taken, and when their structure is controlled at each production phase. Such system allows presentation of a positive impact of the plant on the environment, to estimate a contribution of each division to the general influence, to control the sewage formation process and to operate production in order to reduce the impact on environment. There is a possibility of forecasting the qualitative and quantitative composition of sewage for any period in all divisions of the enterprise, which is an essential addition to the laboratory methods of analysis, which not always are indicative, demand time, not all elements of a substance can be defined.

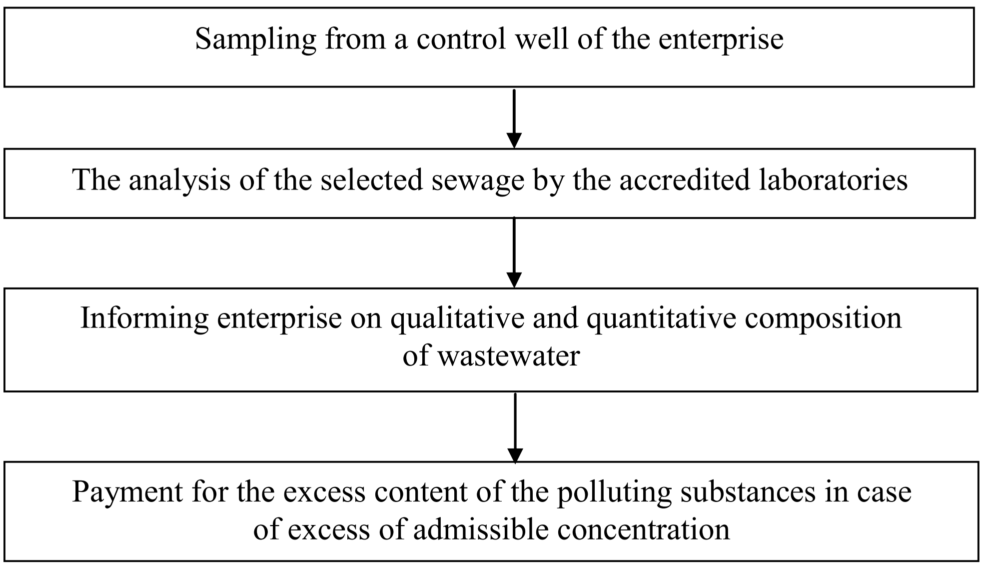


Fig. 1**.** The present wastewater control system in Ukraine

For modernization of the wastewater control system there was a need of studying of the technological scheme of production. Analysis of the beer production process on Mykolaiv Branch of "SUN InBev Ukraine" showed the main points of wastewater formation:

1. Reception of barley and malt; there isn’t using of chemicals and dumping of industrial sewage.

2. Barley crushing; there isn’t using of chemicals and dumping of industrial sewage too.

3. Preparation of water for beer production: chemicals for reduction of water in the corresponding quality are used.

4. Preparation of beer wort consists of the following stages:

– grout extraction of malt's soluble substances and transformation under the influence of enzymes of insoluble substances;
– filtration separation of beer mash from a pellet. Mash and insoluble substances in water - a pellet is received (*Kovalevskaya, 1993*).
– mash boiling with hop. Mash comes to the machine where hopes are added and boiled. Mash is sterilized during cooking; enzymes are inactivated; bitter substances of hop are dissolved in mash, proteins coagulate (*Kolotylo et al., 2003*).
– separation from hop and cooling (*Kovalevskaya, 1993*).

The sewage containing organic pollution, particles of diatomaceous earth, a pellet and the dissolved components of detergents are respectively formed.

5. Mash is fermented. Special races of cultural yeast are used in brewing which ferments mash with formation of alcohol and carbon dioxide (*Kunce 2001*). Fermentation takes place in two stages:

– main fermentation. It is characterized by intensity of the process and fermentation of the most part of sugars (a maltose, glucose, fructose and others);
– young beer is cooled for the best sedimentation of yeast and transferred for the subsequent main fermentation.

The waste, containing organic pollution, shares of yeast, pellets, beer and dissolved components of detergents are respectively formed.

6. Ready beer is filtered on the kizelgur filters. For beer which is spilled in barreled, use separations. At this stage water and detergents are used, the sewage containing components of the used means and organic pollution is formed (*Kunce, 2001*).

7. Preparation of a container and beer barreling: water for washing a container with the use of the aggressive washing substances. The sewage were sated with various aggressive substances from the remains of labels gets to the sewage, flew down and so forth.

8. Department of quality control of beer. A number of chemicals which are necessary for determination of quality indicators of the ready-made product, mash, malt, water and so on are used. Insignificant pollution of very low concentration gets to sewage.

9. Department of logistics: low-quality beer merges in the sewerage that means high organic pollution.

10. Auxiliary production: water is also used for economic domestic needs.

The carried-out analysis allows determination of the main divisions polluting sewage such as department of brewing, including filtration, packing and logistics. Therefore it is necessary to study the means that are used in these divisions, and what polluting substances compose the sewage. The brewing department uses a number of chemicals and means. At the brewing stage: solution of nitric acid HNO_3; solution of phosphoric acid H_3PO_4; solution of sodium hydroxide NaOH; P3-stabicip OXI; P3-topactive 200; at the stage of fermentation and filtration of beer: solution of nitric acid HNO_3; solution of sodium hydroxide NaOH; P3-oxonia active 150; P3-topax 66; P3-oxonia; P3-trimeta DUO; Hlorantoin; P3-ansep CIP. The mentioned substances get to the sewage together with organic pollution: shares of the yeast; extract losses; beer losses; diatomaceous earth shares; share pellet.

The packaging department of uses the following materials: solution of phosphoric acid H_3PO_4; solution of nitric acid HNO_3; solution of sodium hydroxide NaOH; P3-oxonia active; P3-topax686; P3-topax 56; P3-stabilon WT; P3-oxonia; P3-stabilon plus; P3-topactive 200; P3-topactive DES; DryExx; P3-polix XT; P3-lubodrive; P3-oxonia active 150; P3-ansep CIP.

The Logistics department conducts regular showers substandard products.

The chemical composition of means which are used by enterprise were studied. For example, detergent P3-topax56 is characterized by the following composition: H_3PO_4 25 30%; 2-(2-butoksyetoksy) ethanol – 2,5%; surfactant (alkylaminoxides) – 2,5%; P – 9,6 %, N 0,18%, COD 170 mg O_2/g. Similar results obtained for all means, but we choose to calculate the average amount of each substance content.

The technological scheme of production with the image of the main stages is made for modernization of wastewater control system. We will represent all necessary resources, chemicals and means which are used in the enterprise and which as a result can get to the composition of sewage in Fig. 2. Thus technological operation is "a black box" for us. We are interested in only those substances which are on the entrance and at the exit at the technological process.

At the exit, wastewater will be full of those substances that are used in the company at a particular time. Besides, from the brewing department the remains of beer, yeast, diatomaceous earth, a pellet and extract get to the sewage. Their structure may be different, however, for calculation we use their average data given to contents of nitrogen, phosphorus and COD.

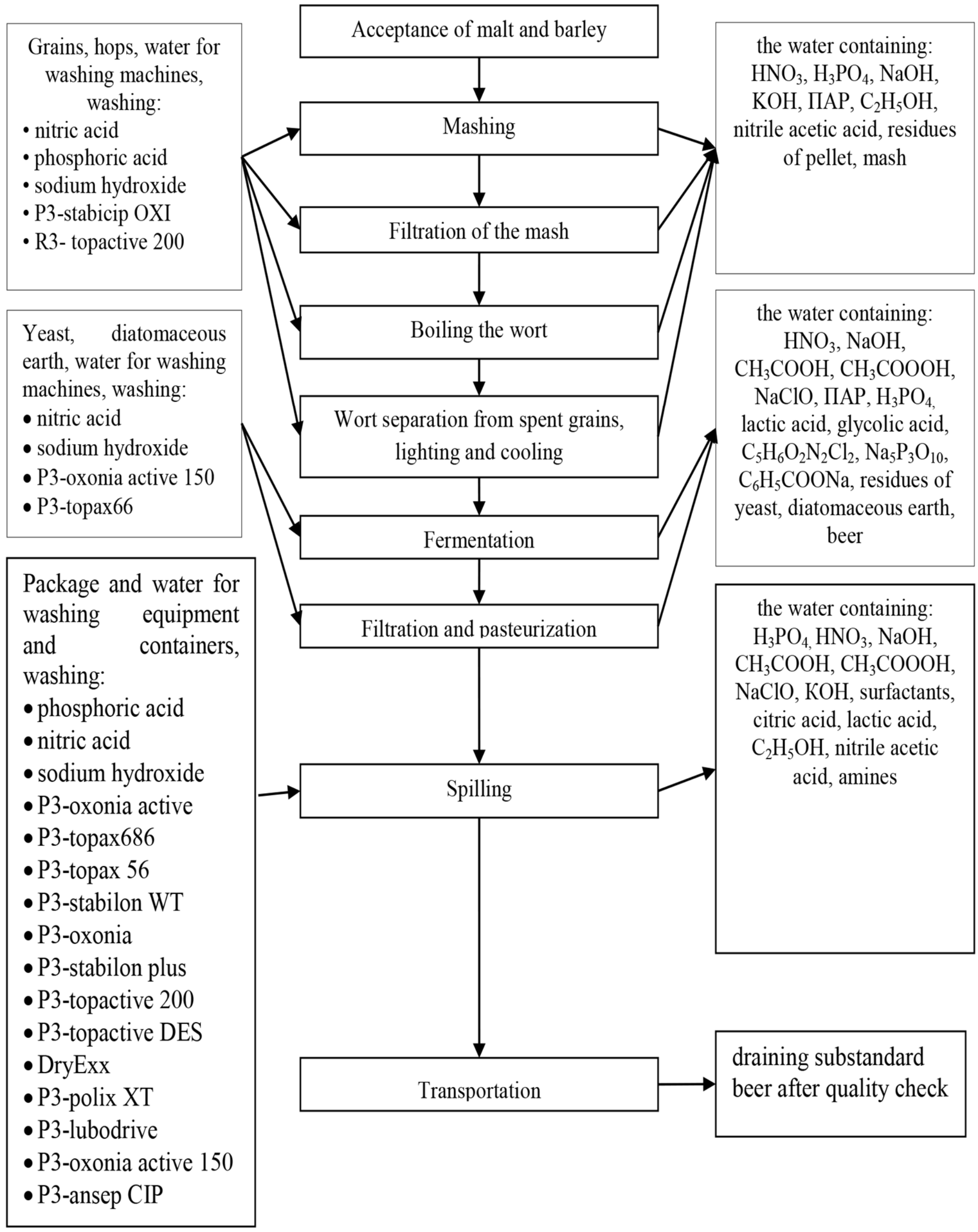


Fig. 2. Scheme of wastewater formation

Analyzing the composition of the means used at the enterprise, the structure of organic pollution, and the Rules of Admission of Sewage in the Municipal Sewerage of the City to control composition of sewage, we choose the following indicators:

- COD – this indicator is given for all used means, and also for organic pollution. It is an integrated and informative indicator of waters pollution (*Muravyov, 2004*);
- phosphates are a part of some means;
- surfactants are part of some means;
- nitrogen content calculated by the nitrate form, as part of some assets is nitric acid.

Nitrogen in the ammonium and nitrite form, regulated by the Rules, is not contained in the compounds, but it is a part of organic matter, and then can go into the ammonia, nitrite and nitrate form. Based on this we also take into account the total content of nitrogen.

As daily calculation is made generally to know the load of local treatment facilities, it is necessary to consider also the general content of phosphorus. Therefore this indicator will also enter the calculations.

The analysis of structure of the used substances shows that the numerous amounts of chemicals are their part. All these substances will be presented in the form of certain indicators: COD, phosphates, surfactants, nitrates, general nitrogen.

The calculation procedure is presented by the list of actions. The example is given for one month.

1) To determine the mass of a pollutant using the formula 1:

$$m(pollut.) = w(pollut\_in\_mean) \cdot m(mean) = \\ = \frac{M(pollut\_in\_subst)}{M(subst)} \cdot w(subst\_in\_mean) \cdot m(mean), g \qquad (1)$$

where *M* (*pollut_in subst.*) the molar mass of the pollutant in the substance [g/mol], *M* (*subst*) the molar mass of the substance [g/mol], *w* (*subst_in mean*) mass fraction of substance containing pollutants in means, *m* (*mean*) the mass of the used means [g].

Calculation was performed for each of the selected pollutants, determining the mass of phosphate, nitrate, total nitrogen, surfactants, COD and for each mean used in departments: brewing, packaging and logistics. For example, to find the mass of phosphates, we determine their weight in each substance which contains phosphates. In the brewing department of phosphates contain only in P3-trimeta DUO in the form of phosphoric acid. For example we find the mass of phosphates using the formula 1 if we know the mass of means and a share of phosphoric acid:

$$m(\mathrm{PO_4^{3-} in\ P3\text{-}trimet\ a\ DUO}) = \frac{95\,kg/kmol}{98\,kg/kmol} \cdot 0{,}4 \cdot 525\,kg = 203{,}57\,kg$$

Similarly for department of packing:

$$m(\mathrm{PO_4^{3-} in\ H_3PO_4}) = \frac{95\,kg/kmol}{98\,kgkmol} \cdot 0{,}54 \cdot 490\,kg = 256{,}5\,kg$$

$$m(\mathrm{PO}_4^{3-}\text{in P3 - topax 56}) = \frac{95\,kg/kmol}{98\,kg/kmol}\cdot 0{,}275\cdot 8kg = 2{,}1kg$$

$$m(\mathrm{PO}_4^{3-}\text{in P3 - stabilon plus}) = \frac{95\,kg/kmol}{98\,kg/kmol}\cdot 0{,}075\cdot 286\,kg = 20{,}8kg$$

COD indicator for each means is given in kg O_2/kg, and the mass of means is considered in kg. Therefore COD for various means is determined by a formula 2:

$$COD_{tot.mean} = COD_{mesn}\cdot m_{mean}\cdot 10^{-3},\ kg\ O_2 \quad (2)$$

For organic pollution we use the accepted data, considering the formula 3:

$$COD_{tot.substance} = COD_{substance}\cdot m_{substance,}\ ,\ kg\ O_2\ . \quad (3)$$

To calculate the COD for the brewing department one should consider the following substances: P3-topax66, P3-trimeta DUO, P3-ansep CIP, and the remains of diatomaceous earth, yeast extract and beer pellet that enter the wastewater.

2) Determine the total mass of a particular pollutant in the department and across the entire enterprise according formula 4.

$$\Sigma m(pollutant) = \Sigma m(pollutant_{d.brewing.}) + \Sigma m(pollutant_{d.packaging.}) + $$
$$+ \Sigma m(pollutant_{d.logistics.}), \quad (4)$$

where $\Sigma\ m(pollutant_{d.brewing.})$, $\Sigma\ m(pollutant_{d.packaging.})$, $\Sigma m(pollutant_{d.logistics.})$ the total weight of a particular pollutant for a specific branch, consisting of a mass of pollutant in each mean.

Here is an example of determining the total mass of pollutants (in the example phosphates).

$$\Sigma PO_4^{3-}\ (dep.brewing) = PO_4^{3-}\ (P3\text{-}trimeta\ DUO).$$

$$\Sigma PO_4^{3-}\ (dep.brewing) = 203{,}57\ kg.$$

$$\Sigma PO_4^{3-}\ (dep.packaging) = PO_4^{3-}(H_3PO_4) + PO_4^{3-}(P3\text{-}topax\ 56) + PO_4^{3-}(P3\ stabilon\ plus).$$

$$\Sigma PO_4^{3-}\ (dep.packaging) = 256{,}5\ kg + 2{,}1kg + 20{,}8kg = 279{,}4\ kg.$$

Determine the total mass of phosphate across the enterprise:

$$\Sigma m(PO_4^{3-}) = 203{,}57\ kg + 279{,}4\ kg = 482{,}97\ kg.$$

A similar calculation was performed for determination of COD:

$$\Sigma COD\ (dep.brewing) = COD(P3\text{-}topax66) + COD(P3\text{-}trimeta\ DUO) + COD(P3\text{-}ansep\ CIP) + COD(fulfilled\ yeast) + COD(fulfilled\ diatomaceous\ earth) + COD(pellet) + COD(beer\ extract);$$

$$\Sigma COD(dep.brewing) = 10^{-3}\cdot(99\ kg\ O_2/g\cdot 176\ kg + 250\ kg\ O_2/kg\cdot 525\ kg) + 4818\ kgO_2/kg\cdot 55000\ kg + 16500\ kg\ O_2/l\cdot 1100\ l + 2400\ mg\ O_2/l\cdot 600\ l + $$
$$+ 100\ 000 mgO_2/l\cdot 349575\ l = = 35403{,}714\ kg\ O_2;$$

$$\Sigma COD\ (dep.packaging) = COD(P3\text{-}topax\ 56) + COD\ (P3\text{-}stabilon\ WT) + $$
$$+ COD\ (P3\ stabilon\ plus) + COD\ (P3\text{-}topactive\ 200) + COD\ (P3\text{-}topactive\ DES) +$$

+ *COD* (*DryExx*) + *COD* (*P3-polix XT*) + *COD (P3-lubodrive)* +
+ *COD* (*P3-ansep CIP*) + *COD* (*P3-topax66*);

$$\Sigma\, COD\ (dep.packaging) = 10^{-3}\cdot(170\ kg\ O_2/kg \cdot 8\ kg + 155\ kg\ O_2/kg \cdot 16\ kg + 970 kg O_2/kg \cdot 286 kg + 155\ kg\ O_2/kg \cdot 265\ kg + 240\ kg\ O_2/kg \cdot 20\ kg + 20\ kg\ O_2/kg \cdot 463\ kg + 180\ kg\ O_2/kg \cdot 240\ kg + 790\ kg O_2/kg \cdot 3\ kg + 16\ kg\ O_2/kg \cdot 464\ kg + 99 kg\ O_2/kg \cdot 201\ kg) = 366{,}1312\ kg\ O_2;$$

$$\Sigma COD\ (dep.logistics) = COD(sub\text{-}standard\ beer),\ beer\ density\ 1.1\ kg/l;$$

$$\Sigma COD\ (dep.logistics) = 0{,}400000\ kg\ O_2/kg \cdot 16556\ l \cdot 1{,}1\ kg/l = 7284{,}64\ kg\ O_2;$$

$$\Sigma\, COD = \Sigma COD\ (dep.brewing.) + \Sigma COD\ (dep.packaging) + \Sigma COD\ (dep.logistics);$$

$$\Sigma\, COD = 43054{,}4852\ \text{kg}\ O_2.$$

We use similar formulas for other pollutants, including the mass of use of substances and organic waste.

3) To determine the concentration of pollutants using the formula 5:

$$c(pollut) = \frac{\sum m(pollut)}{V(wastewater)}, kg/m^3 \tag{5}$$

where Σ *m* (*pollut*) the total mass of pollutants in all substances [kg], *V* (*wastewater*) the amount of wastewater for a certain period [m^3].

Example of calculation of concentration of phosphates (volume of wastewater is 14779 m^3):

$$c(\mathrm{PO_4^{3-}}) = \frac{482{,}97 kg}{14779 m^3} = 0{,}03267 kg/m^3$$

The indicator of COD is normalized of kg O_2/m^3, and for substances is given in mg O_2/g, therefore for reduction to one dimension we use a formula 6:

$$COD_{total} = \frac{\Sigma COD\,(pollut)}{V(wastewater)\cdot 10^6}, kgO_2/m^3 \tag{6}$$

$$COD_{totaly} = \frac{4305448520\ 0}{14779 \cdot 10^6} = 2{,}91322, kgO_2/m^3$$

This calculation is performed for nitrate, total nitrogen and surfactants. We carry out other calculations in a software package of MS Excel.

4) To predict the level of pollution and to make the relevant decisions, for each substance we determine the planned volume of its usage, and also we can compare the planned norm of use with a real volume. Such tool allows fast identification of the main sources of pollution, those departments which exceed the norms of use and to taking measures for rapid response to reduction of impact on the environment. For this purpose in calculation we will define not only the actual volume of use of means, but also the planned one. For determination of the planned mass of use of a certain means we use a formula 7:

$$m_{planned} = norma \cdot V_{panned.bear}, \tag{7}$$

where norma – the rate of use of a specific product [kg·hl^{-1}], $V_{planned.besr}$ – the amount of beer that planned release [hl].

Here is an example of calculation for the brewing department of nitric acid, $V_{planned.bear}$=78930hl:

$$m_{planned}(HNO_3) = 0,07\ kg{\cdot}hl^{-1} \cdot 78930ch=5525,1kg$$

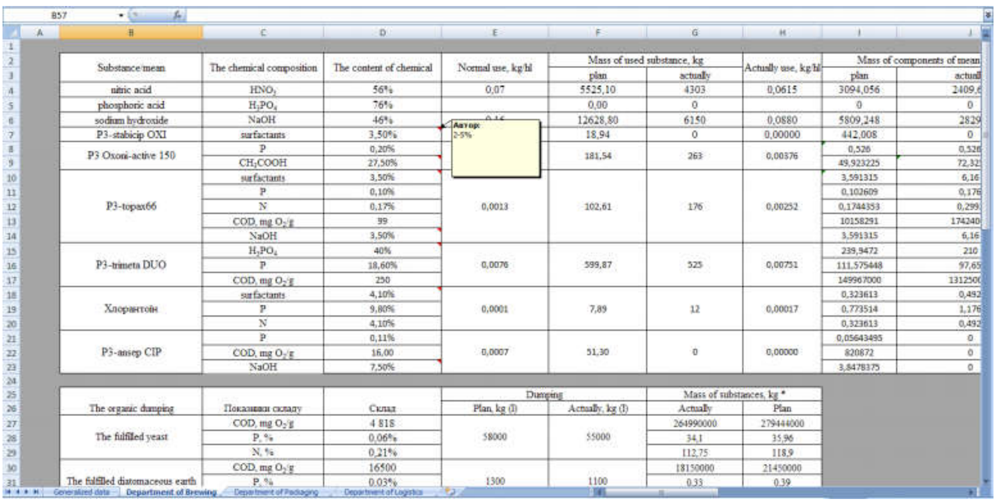
To calculate the actual number of specific product *(X)* per a production unit use the formula 8:

$$X = \frac{m_{actual}}{v_{fact.beer}}, \tag{8}$$

where m_{actual} – the actual mass of the used means [kg], $V_{actual\ beer}$ – the volume of beer actually released [hl].

5) The result is the generalized data where the mass of the polluting substances on departments, their total mass and concentration are specified.

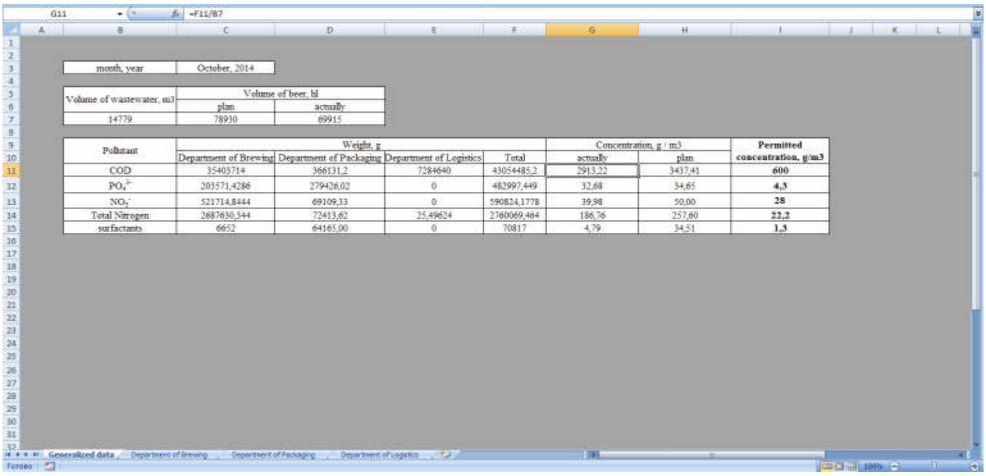
To show viability and effectiveness of a similar calculation we show the obtained data in the form of the schedule. For three departments and the general, and also the model of its work is given in Fig. 3,4 and 6. Fig. 5 shows the calculated COD for the selected period indicating the volume of beer produced.



Substance/mean	The chemical composition	The content of chemical	Normal use, kg/hl	Mass of used substance, kg		Actually use, kg/hl	Mass of components of mean	
				plan	actually		plan	actual
nitric acid	HNO_3	56%	0,07	5525,10	4303	0,0615	3094,056	2409,6
phosphoric acid	H_3PO_4	76%		0,00	0		0	0
sodium hydroxide	NaOH	46%	0,16	12628,80	6150	0,0880	5809,248	2829
P3-stabicip OXI	surfactants	3,50%		18,94	0	0,00000	442,008	0
P3 Oxoni-active 150	P	0,20%		181,54	263	0,00376	0,526	0,526
	CH_3COOH	27,50%					49,923225	72,32
P3-topax66	surfactants	3,50%	0,0013	102,61	176	0,00252	3,591315	6,16
	P	0,10%					0,102609	0,176
	N	0,17%					0,1744353	0,299
	COD, mg O_2/g	99					10158291	174240
	NaOH	3,50%					3,591315	6,16
P3-trimeta DUO	H_3PO_4	40%	0,0076	599,87	525	0,00751	239,9472	210
	P	18,60%					111,575448	97,65
	COD, mg O_2/g	250					149967000	1312500
Хлорантоїн	surfactants	4,10%	0,0001	7,89	12	0,00017	0,323613	0,492
	P	9,80%					0,773514	1,176
	N	4,10%					0,323613	0,492
P3-ansep CIP	P	0,11%	0,0007	51,30	0	0,00000	0,05643495	0
	COD, mg O_2/g	16,00					820872	0
	NaOH	7,50%					3,8478375	0

The organic dumping	Показники складу	Склад	Dumping		Mass of substances, kg *	
			Plan, kg (l)	Actually, kg (l)	Actually	Plan
The fulfilled yeast	COD, mg O_2/g	4 818	58000	55000	264990000	279444000
	P, %	0,06%			34,1	35,96
	N, %	0,21%			112,75	118,9
The fulfilled diatomaceous earth	COD, mg O_2/g	16500	1300	1100	18150000	21450000
	P, %	0,03%			0,33	0,39

Fig. 3. A fragment of calculating the concentration of pollutants in MS Excel



month, year	October, 2014

Volume of wastewater, m3	Volume of beer, hl	
	plan	actually
14779	78930	69915

Pollutant	Weight, g				Concentration, g / m3		Permitted concentration, g/m3
	Department of Brewing	Department of Packaging	Department of Logistics	Total	actually	plan	
COD	35403714	366131,2	7284640	43054485,2	2913,22	3437,41	**600**
PO_4^{3-}	203571,4286	279426,02	0	482997,449	32,68	34,65	**4,3**
NO_3^-	521714,8444	69109,33	0	590824,1778	39,98	50,00	**28**
Total Nitrogen	2687630,344	72413,62	25,49624	2760069,464	186,76	257,60	**22,2**
surfactants	6652	64165,00	0	70817	4,79	34,51	**1,3**

Fig. 4. A fragment of calculating the concentration of pollutants in MS Excel

Similar calculation was checked for the period January 2012-October 2014. To show viability and effectiveness of similar calculation we show the obtained data in the form of the schedule. Fig. 5 shows the calculated COD for selected period indicating the volume of beer produced.

Such calculation is necessary to exercise control of compliance to admissible concentration not to be relied by single analyses which often happen inexact, for decision-making and modification of the technological processes, for adaptation of the technological process of production to new requirements, for the best representation of an overall picture of activity of the enterprise.

However, this calculation can be made for any period, knowing the mass of the used means and the dumped organic waste in wastewater. If the enterprise has own treatment facilities of biological type, it's important to control not only the general streams of substances at the enterprise and real concentration of the polluting substances in sewage (that reflects only average values of month). There is a need to know actual information on what processes happen in each department at the present time to predict qualitative and quantitative composition of the wastewater arriving on treatment facilities. If such information is known, it is possible to optimize of wastewater control system.

Such a determination can be made for current expenses and beer production to receive operational results on composition of wastewater during a certain period of time. The general principle of the calculation is the same as to calculate the concentrations of pollutants in a month, but we carry out accent on organic to loading which is a key indicator for work of treatment facilities.

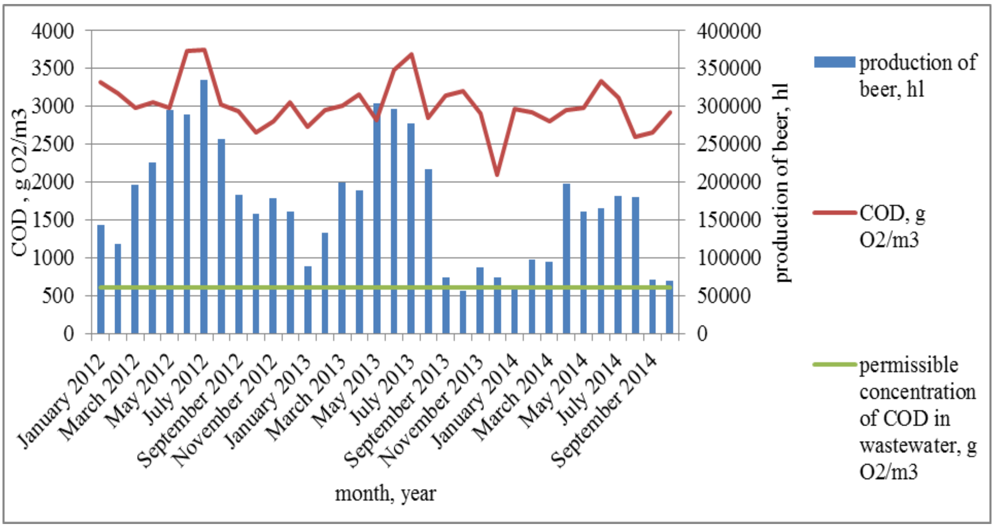
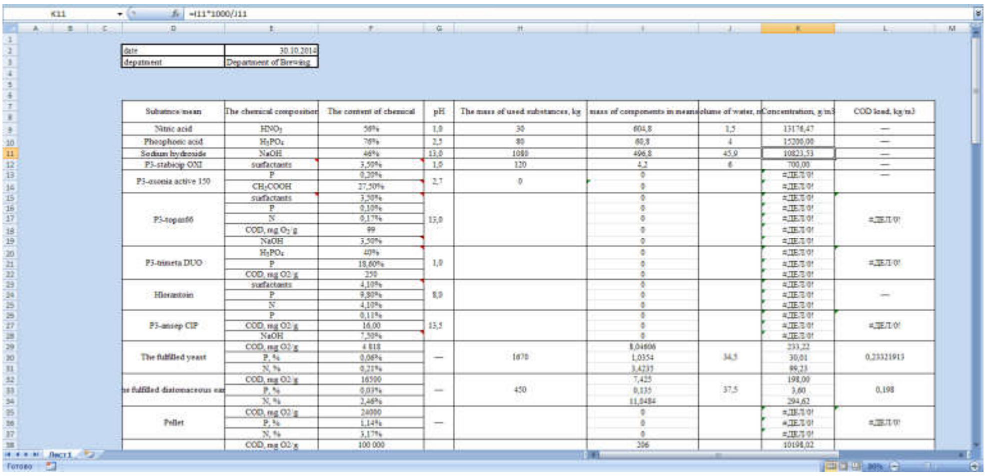


Fig. 5. Calculated of COD in wastewater of Mykolaiv Branch of "SUN InBev Ukraine", January 2012 - October 2014



date	30.10.2014
depatment	Department of Brewing

Substance mean	The chemical composition	The content of chemical	pH	The mass of used substances, kg	mass of components in means	olume of water, m	Concentration, g/m3	COD load, kg/m3
Nitric acid	HNO_3	56%	1,0	30	604,8	1,5	13176,47	—
Phosphoric acid	H_3PO_4	76%	2,5	80	60,8	4	15200,00	—
Sodium hydroxide	NaOH	46%	13,0	1080	496,8	45,9	10823,53	—
P3-stabicip OXI	surfactants	3,50%	1,0	120	4,2	6	700,00	—
P3-oxonia active 150	P	0,20%	2,7	0	0		#ДЕЛ/0!	—
	CH_3COOH	27,50%			0		#ДЕЛ/0!	
P3-topax66	surfactants	3,50%	13,0		0		#ДЕЛ/0!	#ДЕЛ/0!
	P	0,10%			0		#ДЕЛ/0!	
	N	0,17%			0		#ДЕЛ/0!	
	COD, mg O_2/g	99			0		#ДЕЛ/0!	
	NaOH	3,50%			0		#ДЕЛ/0!	
P3-trimeta DUO	H_3PO_4	40%	1,0		0		#ДЕЛ/0!	#ДЕЛ/0!
	P	18,60%			0		#ДЕЛ/0!	
	COD, mg O2/g	250			0		#ДЕЛ/0!	
Hlorantoin	surfactants	4,10%	8,0		0		#ДЕЛ/0!	—
	P	9,80%			0		#ДЕЛ/0!	
	N	4,10%			0		#ДЕЛ/0!	
P3-ansep CIP	P	0,11%	13,5		0		#ДЕЛ/0!	#ДЕЛ/0!
	COD, mg O2/g	16,00			0		#ДЕЛ/0!	
	NaOH	7,50%			0		#ДЕЛ/0!	
The fulfilled yeast	COD, mg O2/g	4 818	—	1670	8,04606	34,5	233,22	0,23321913
	P, %	0,06%			1,0354		30,01	
	N, %	0,21%			3,4235		99,23	
he fulfilled diatomaceous ea	COD, mg O2/g	16500	—	450	7,425	37,5	198,00	0,198
	P, %	0,03%			0,135		3,60	
	N, %	2,46%			11,0484		294,62	
Pellet	COD, mg O2/g	24000	—		0		#ДЕЛ/0!	#ДЕЛ/0!
	P, %	1,14%			0		#ДЕЛ/0!	
	N, %	3,17%			0		#ДЕЛ/0!	
	COD, mg O2/g	100 000			206		10198,02	

Fig. 6. A fragment of calculation of concentration of the pollutants in one day in MS Excel

There are restrictions on organic loading that treatment facilities optimum worked. There are restrictions on organic loading that treatment facilities optimum worked. So, maximum daily loading is 14000 kg COD/day for treatment facilities of the studied plant. Considering the volume of the anaerobic reactor, it is also defined restriction on unit of volume of sewage 8,64 kg of COD/m^3. This indicator can be calculated in advance. In calculation we have data of concentration of COD in g/m^3. Therefore, we use a formula:

$$COD_{load} = \frac{COD}{1000},\ kg/m^3, \tag{9}$$

where COD – COD of the concrete wastewater arriving on cleaning [g/m^3], 1000 – transfer coefficient from g to kg.

Data of use of means and organic substances discharges within one day are provided for each process and summarized in the table. Thus for each means we give value pH for the illustration of specifics of wastewater.

Such calculation is necessary to exercise control of compliance to admissible concentration not to be relied by single analyses which often happen inexact, for decision-making and modification of the technological processes, for adaptation of the technological process of production to new requirements, for the best representation of an overall picture of activity of the enterprise.

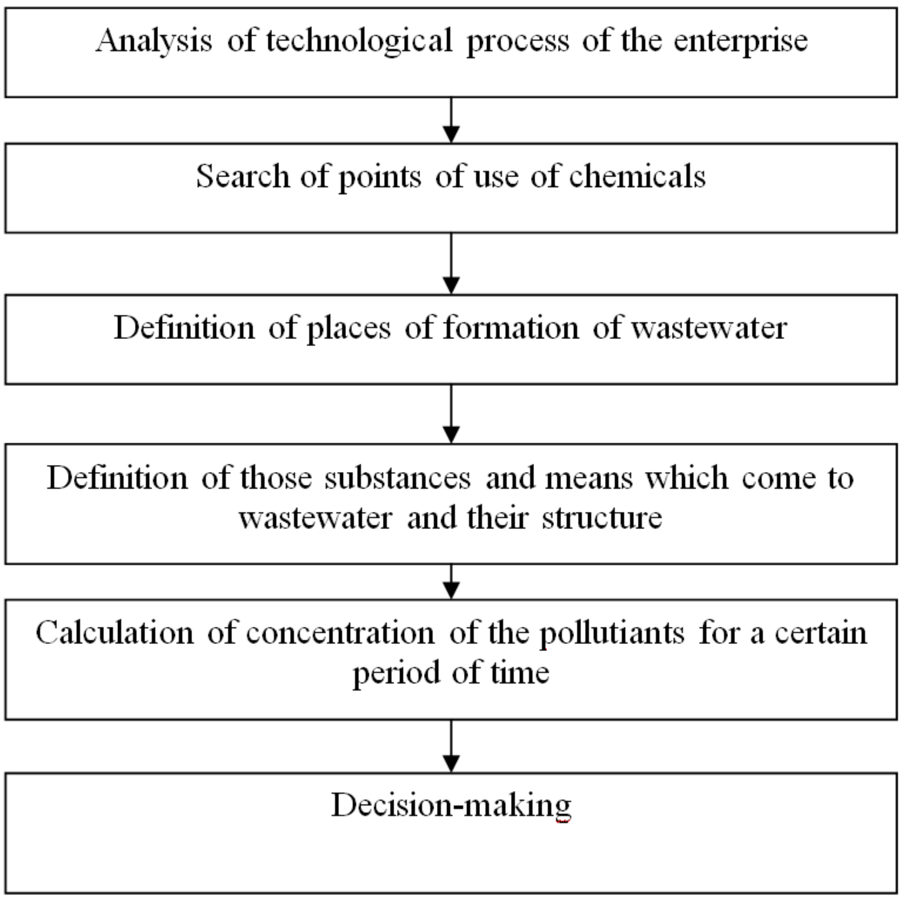


Fig. 7. The offered control system of wastewater' formation.

Thus, the proposed system of calculation of concentration of the pollutants is the additional effective instrument of the wastewater control system of the plant, allows identification of the processes that causes the most pollution (*Mitryasova et al., 2015*). This system allows making decisions on reduction of influence on environment by change or improvement of production process, replacing some means so on (Fig. 7).

3 Summary and Conclusions

The main problem of the plants of the brewing industry is the use of a great amount of water and formation of the wastewater polluted by various substances. The pollutants consist of a pellet, diatomaceous earth, yeast, beer remains, etc., and also components of those means which are used in the plant in the certain period of time. The wastewater control system has the stating character: single tests at the exit from the enterprise one time a week are investigated, and then it is determined if the company complies with the standards, but this approach is not quite correct. Therefore, there is a need to carry out a continuous wastewater control by introduction of the new tool on the basis of calculation of the pollutants concentration.

The system has a number of functions:

- illustrative, as it shows all production processes and gives a better picture of the overall impact on the environment;
- controlling, as calculation shows the stage on which of the process the most waste water is generated, which unit is the biggest polluter; the result is valid, not single concentration of pollutants;
- predicting: by data of the use norms of means and of the planned quantity of production, we can expect the qualitative and quantitative composition of wastewater at the exit from each department and from the enterprise in general;
- management, after all, on the basis of the analysis of the obtained data on processes which make the greatest pollution, it is possible to make operational decisions on reduction of impact on environment;
- informative: provided data on the concentrations of substances, including those that are not controlled by laboratory methods.

The recommended system is not intended to replace the laboratory analysis. It is the additional effective wastewater control instrument. It may be adapted for any other production. When local treatment facilities of biological type works, there is a need of exact control over the qualitative and quantitative composition of the wastewater. Therefore the given control system is adapted for daily calculations of the pollutants concentration in sewage. This allows making quick decisions on the treatment of specific wastewater, which significantly reduces the negative impact on the environment.

References

1. International Finance Corporation (IFC), Environment, Health & Safety Guidelines. Food and Beverage Processing, April 2007.
2. International Organisation for Standardisation (ISO) www.iso.org ISO14001:2004: Environmental Management Systems – Requirements with Guidance for use. Geneva: ISO ISO22000:2005: Food Safety Management System – Requirements for any organisation in the food chain. Geneva ISO
3. ISO 14040. Environmental management - Life cycle assessment - Principles and framework, 2006.
4. Kolotylo D. M., Sokolovsky A. T., Garbuz S.V. etc.: Technological Processes of Industries. Kyiv, KNEUб, 2003.
5. Kovalevskaya L. P.: General Technology of Food Manufactures. Moscow, Kolos, 1993.
6. Kunze B.: Technology of Malt and Beer. Translated from the German. St. Petersburg, Profissiya, 2001.
7. Lebedevych S. I.: Theoretical and methodological basis for the formation of sector environmental management system of enterprises. Lviv: Liga-Pres (in Ukr.), 2008.
8. Mitryasova O., Pohrebennyk V., Bogatel N.: Enterprises' management of wastewater**.** International scientific conference, New Trends in Ecological and Biological Research», September 9th–11th, 2015, University of Prešov in Prešov, Slovak Republic. – Prešov, 2015, P. 22.
9. Muravyov A. G.: Guidelines for the Determination of Water-quality by Field Methods. St. Petersburg, Christmas, ISBN 5-89495-113-5, 2004.
10. Rockstrom J., M. Falkenmark L. Karlberg H. Hoff S. Rost and D. Gerten.: Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resources Research*, 45, 1–16, 2009.
11. Rules of Admission of sewage in the municipal sewerage Mykolaiv. Mykolaiv: Mykolaiv city council. Executive committee, 2003.
12. Rules of Admission of sewage of the enterprises in municipal and departmental systems of the sewerage of settlements of Ukraine. 19.02.2002 No. 37.
13. Rules of protection of a surface water from pollution by sewage. 25.03.1999 No. 465.
14. The Guide to Environmental, Health and Work Protection for Brewing Production, 2007.
15. United Kingdom (UK) Environment Agency. Food and Drink Sector Guidance Note IPPC S6.10. 2003.
16. Water Code of Ukraine from 06.06.1995 № 213/95-ВР.

Information support of conception of environmental safety of water supply and wastewater treatment

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Abstract

The present study analyzes ecological and technological aspects of functioning of water supply and wastewater treatment in the natural environment. Social and environmental aspects of relationship between water management structures and natural systems caused by duality of direct and indirect impact on man were actualized. The environmental safeties concept of natural and technogenic system "environment - water supply - wastewater treatment - man" was scientifically substantiated. The article presents algorithm's structural schemes of environmental safety's analyzing and implementation of water supply and treatment. Established methodological premises of ecological safety of water supply and wastewater treatment include formulation of axioms, principles and system integrators laws. The research methodology of supply security components was defined according to hierarchical manner to internally and externally systemic levels of danger with the use of integrated options. New approaches to the formation of management's strategy of environmental safety and wastewater treatment are theoretically grounded. The strategy is aimed at improving the condition of ecosystems and based on mathematical models, information technology and technical solutions. Design tools to improve the environmental safety of the water supply and wastewater treatment by selective water intake and its biological testing are scientifically substantiated.

Keywords

ecological safety, utilities, water supply, wastewater treatment, sewerage, geographic information systems, environmental monitoring

1 Introduction

Environmental safety and water purification is a crucial part public health, environmental and economic development and national security of Ukraine. Menace to national security in the field of water management are worsening the ecological state of natural waters, aggravation of problems of cross border pollution, increasing of risks of accidents at the facilities of water supply and sanitation. Common problems of water security include: exhaustion and degradation of water bodies; ecological status of surface and underground sources of drinking water; high power consumption of supply systems; high water consumption of production processes; depreciation of fixed assets, degradation of technical conditions and high accident rate in engineering communications of water industry; increased risk of industrial accidents; potential menace of complications of sanitary-epidemiological situation in certain areas.

According to the Ukrainian law "About the National Target Program "Drinking water of Ukraine" for 2011-2020", problems of water supply and quality of drinking water are of national strategic importance and require complex solution. One of the modern approaches to solving problems of ecological safety management of water supply and wastewater treatment (ESWSWT- ecological safety of water supply and wastewater treatment) is the use of advanced information technology and geo-information systems (GIS). They provide presentation of different subject matters information in a usable form and favor to the efficiency and justify validity of decisions.

Formulation of scientific problem and its significance

Water resources are key for socio-economic development of Ukraine, ensuring of quality of life and environmental well-being. Urbanization requires quality, uninterrupted and centralized safe water supply and wastewater treatment.

In this branch there is a number of ecological and technological problems whose solution has the essence weight to ensure the environmental safety of water supply and wastewater treatment (*Yatsyk, 2001*).

The key is the stable functioning of water supply systems and high effectiveness of wastewater treatment plants. In particular, these systems have critical equipment obsolescence and limited possibilities of water purification. Essential danger for water objects is caused by reverse of municipal water. Significant risk for outward environment is created by chemical reagents of water treatment plants. Technologies applied in many water supply systems do not conform to the level of pollution of surface sources and they often provide regulatory quality of drinking water. All this requires to improve the situation immediately.

Increasing of human impacts at water bodies causes also need to improve water management development in conditions of risk and uncertainty that is inherent to ecological safety. Many theoretical and practical provisions that developed by the order of industrial branches of economy are not always suitable for direct use in solving environmental problems of modern municipal water management.

Therefore, it is necessary to find new approaches to ensure the environmental safety of water supply systems, which include: development of methodology for studying environmental safety and water purification; renovation of engineering communications of water supply and sewerage; informatization and development of adequate forms of water management systems and wastewater treatment.

Relevance of ESWSWT informatization management process is caused by or ascribable of the need of structuring and unification of the subject area. Current approaches to solving problems of the ESWSWT is the use of information technologies - ways and means of collection, transmission, storage, retrieval, processing and information security focused on implementing management. They are based on the use of telecommunication equipment and related software.

Analysis of recent research on this issue

Analysis of previous baseline studies have shown that many scientists made towards improving the environmental safety factor for water (*Kachynsky, 2001; Yatsyk, 2001; Mokryy, 2003; Vasylenko, 2006; Yakovlev, 2009*). But the work carried out in this area as a rule are generally on objective individual components without their proper systemic processing. Ecological security of urban water supply and water treatment inherent lack of knowledge, lack of a single coherent foundations considering various factors danger. For its successful solution it should be found new theoretical and methodological approaches.

The problems of ecological safety in the field of water management are examined by Loucks (*2005*), Dunbar (*2011*), Wickham (*2011*), Denczew (*2005*) etc.

The analysis of the various aspects of ecological security of water supply and water treatment allows to state that there are significant causal relationships of many diseases of the population with quality of drinking water. Water systems have critical equipment obsolescence and the extremely limited capacity of the water treatment. Sources of drinking water are in danger. Amid a sharp aging of fixed assets volumes of funds for their renovation are reduced. A number of scientists name it a systemic collapse in the centralized water supply, violation of ecological and social laws of its development.

Ecological and technological directivity of water in conjunction with water objects is deepened by Gomely"a (*2007*), Goncharuk et al. (*2006*), Świderska – Bróż (*2007*), Tillman (*2005*), etc.

There is a significant contradiction between the increasing demand for quality water of users and their negative impact on the environment during the return water drainage. Ukraine ranks second in terms of mortality among the developed countries spreading diseases due to use poor quality water that is a real danger to the gene pool of the nation and security of the country. Correction of this situation became a priority of national wide importance and requires urgent adequate solutions. Thus, the ecological security of water supply needs urgently a deeper study of theoretical and methodological foundations and development of scientific bases of its management based on a comprehensive study of the conditions of formation of ecological danger. It requires further improvement of terminological base defining general principles, the use of new information and simulation technologies and technical means.

The aim and objectives The aim of work is to analyze the methodological approaches to environmental safety and municipal water purification. Objective is to study the use of information technology for monitoring and prediction of geologically safe processes related to the work of water and sanitation networks that are necessary to reduce the negative impact of water supply and wastewater treatment on humans and the environment.

2 Materials and Methods

Methods of theoretical studies are based on the principles of scientific knowledge, logic and system analysis, theory of hierarchical systems and systems engineering. Solving of practical problems is based on the methods of identification of systems, information technologies, logical analysis and synthesis of scientific and technical information.

The object of the research is permanent environmentally dangerous processes and phenomenon associated with the functioning of water supply and wastewater treatment systems. The subject of research is the forms of municipal water utility management, information sources and engineering means to ensure the environmental safety of water supply and wastewater treatment.

3 Results and Discussion

According to the results of the analysis of environmental and technological efficiency of applied processes and water treatment schemes, ecological safety of preparation of drinking water includes the system of internally and externally systemic safety. The safety system internally depends on the quality of construction of water treatment plants, and modern operation of modernization. The livelihoods of people, the state and functioning of the environment impact on the external security (*Vasylenko, 2006; 2009*).

Based on a systematic analysis of the functioning of public water systems and communications (*Vasylenko, 2006; 2009*), urban utilities (*Mokryy, 2003*), block diagram of algorithm of environmental safety and water purification for the successive stages were justified: water objects - externally systemic level - water sources and intakes; engineering structures of purification and distribution of water - internally systemic level (Fig.1).

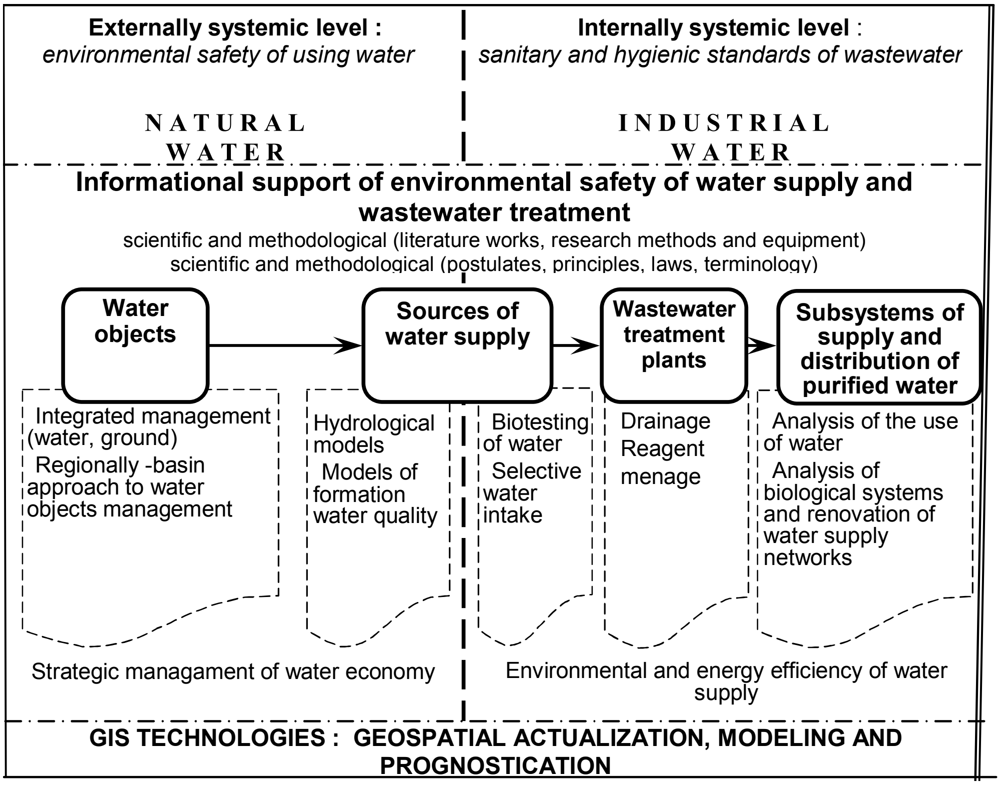

Fig. 1. Block diagram of the algorithm of implementation of the environmental safety water supply and wastewater treatment

Development of scientific and methodological foundations of environmental safety determines axiomatic definition, ecological system integrators methodological principles and patterns that make up a set of theoretical assumptions of solving the problem of environmental security of water supply and wastewater drain (*Vasylenko, 2006; 2009*).

Environmental safety of water supply and sanitation has all the properties of complex dynamic systems. It differs by structuring, interrelation and interdependence of individual elements. Spatio-temporal parameters are characterized by openness, variability, uncertainty and partial uncertainty.

The stability of the system functioning of centralized water supply is defined as the ability to perform its main useful function when the number of consumers and the time for which they receive water of regulatory quality in the required amount does not exceed the acceptable environmental risk. Ensuring of the stability of the system also provides in extreme conditions (natural and man-made disasters, etc.) with secure transfer system for a limited water supply and use of decentralized water supply forms.

The conception of ecological safety of the water supply and wastewater treatment is based on the following basic ecological methodological principles (*Vasylenko, 2006; 2009*).

Methodology of the complexity of solution includes means of implementing environmental security and it is based on the following principles:

The objective principle – harmonization of environmental legislation, approximation production technologies and consumption volume of potable water in accordance with standards of the European Union;

The principle of minimum – ESWSWT increase by changing priorities from capacity increase water pipelines to minimize supply, losses and excessive network water pressure; pipelines damages; unit costs of electricity etc.;

The principle of diversity – to increase system stability for cities life support due to increase species diversity of environmentally safe water supply and functional distribution their compensation capabilities in crisis situations;

Methodology of comprehensiveness solution includes means of realization of environmental safety and it is based on the following principles:

The principle of completeness – ESWSWT content should be coherent system – from a water body to the consumer at all stages of production and use of water;

The principle of conformity – ESWSWT is provided such a design that minimizes industrial risk and it is the simplest to perform its functions, it adequately reacts to external environmental factors and optimal costs of materials and energy;

The principle of prevention – improving of environmental safety on regional and national levels is more expedient and cheaper than temporary removal of implemented danger with material resources' expenditure on water supply safety;

Methodology of ecological limitations determines limiting factors and it is based on the following principles;

The principle of uncertainty – we can not guarantee the water quality and the environmental safety of drinking water because they have stochastic characteristics, but we can increase their probability and we can reduce adverse risks;

The principle of water synergism – the life quality and the environmental human welfare depend not only individual indicators of drinking water's quality but on synergistic effect of total action of chemical and biological components at the same time.

Based on the technical system development laws, the environmentally safe functioning and development of water supply and wastewater treatment systems are being conducted following such system and technical laws:

1. On the completeness of composition, working capacity and coordinated working rhythm of the elements with continuous movement of water through all parts with minimal environmental losses;
2. Improving the system in order to increasing its ideal level;
3. The uneven development of the system components that creates irregular state alteration of their parts and conditions the choice of primary ways of ensuring ESWSWT, first of all, renovating the water supply system as a vulnerable component;
4. The increase of the system dynamics degree and transition to flexible working structures and modes that adapt to environmental changes of the environment;
5. The transition into "the super system" at the level of water objects, which causes an increase of ecological safety of water sources and drinking water intake that are basic components of ESWSWT.

In general, environmental and methodological principles form the priority areas to ensure ESWSWT, system and technical laws imply the organization of its scientific development and technical implementation.

Within the scope of ESWSWT problems structuring and according to the results of theoretical studies (*Kachynsky, 2001; Vasylenko, 2006; Yakovlev, 2009; Yatsyk, 2009*), the structural and functional scheme of the concept of environmental safety of urban water supply and drainage systems has been presented, and it has been realized in a hierarchical manner (Fig. 2).

Water supply safety is defined as a state of human and biota protection from water supply and drainage system activities that are provided by technical and sanitary safety. Technical water supply safety is a complex of organizational and technical measures to implement the uninterrupted supply of necessary drinking water in standard mode and emergency situations; the ability of water supply objects to sustainable development in the context of internal and external threats, as well as actions of factors that are difficult to be predicted. Sanitary-hygienic water supply safety is an ability of water supply systems to carry out hygiene requirements for water quality at the points of its consumption; state of human protection from disease risk associated with the use of poor quality water.

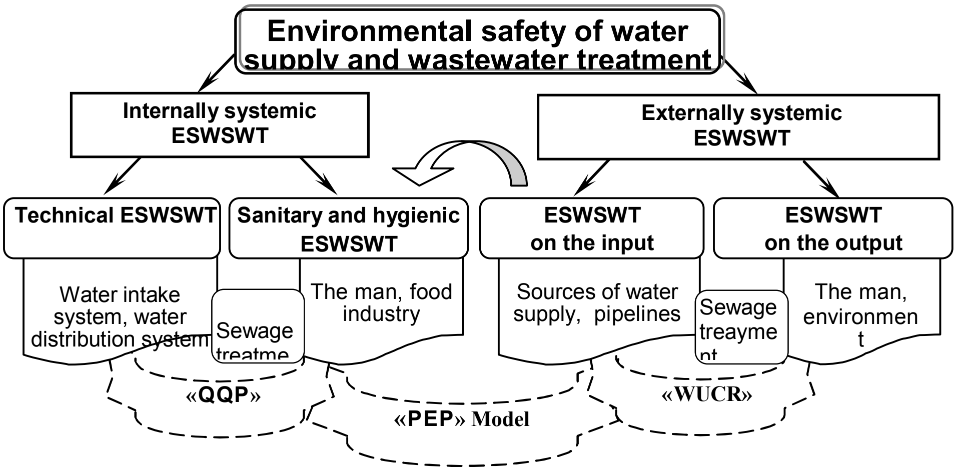

Fig. 2. Structural and functional diagram of conception of ecological safety of urban water supply and wastewater treatment

According to Figure 2, an integrated parameter "QQP" (quality, quantity, pressure), or conditional efficiency factor of water supply systems has been assumed as a basis of quantitative measure of internal security of water supply.

In the first approximation to its assessment the following formula has been proposed:

$$QQP=\prod_{i=1}^{3}\eta_i=\prod_{i=1}^{3}\left[u_i^{\theta_{1i}}\cdot 1(1-u_i)+\frac{1(u_i-1)}{1+\theta_{2i}(u_i-1)^2}\right], \quad (1)$$

where $u_i = \{u_1, u_2, u_3\}$ – dimensionless variables, that characterize water quality - **c**, consumption (quantity) of water - **q** and water pressure - **p** relative to their optimal values, $1(\xi) = \{0,\ \xi < 0;\ ½,\ \xi < 0;\ 1,\ \xi > 0\}$ – a symmetric single function, $\theta_{1i}, \theta_{2i} > 0$ – η_i curves parameters to describe the variables u_i from oval to peak forms.

With the increase of u_i consuming characteristics, the “QQP” parameter increases at first and then decreases. It is recommended to choose water quality $\theta_{11}> 50$. Values of these parameters is empirically defined for peak shapes of curves η_i.

Aggregation of three diverse variables into a single integrated index-indicator makes it easy and reasonable to compare complex water supply systems concerning individual buildings, neighborhoods and whole cities.

A key component of gross domestic product in the water supply system is water in monetary and material terms. Therefore, by analogy with "QQP" an indicator “WUCR” (water use, water consumption, reprocessing) or conventional gross domestic product of water supply is defined as a system-defined parameter of ESWW.

It is assessed according to the results of economic activity through voluminous quantities of water intake Q_i from water sources: $Q_i=Q_c+Q_r+Q_l$, where Q_c - implementation of water to consumers, Q_r - reverse flow of water from building air-conditioning, Q_l - water loss during transportation. Besides that Q_c - useful part of WUCR, which is aimed at meeting the needs of the population; (Q_r+Q_l) - "harmful" component of WUCR ("export in the environment"), which causes undesirable consequences for people and the environment.

The complex system-model "PEP" (population, ecology - economy - energy efficiency, policy - law), or new environmental and economic policy of supply has been introduced. It implies providing consumers with drinking water, based on economically acceptable level of water consumption, increase of energy efficiency and reducing negative consequences for people and the environment, which is based on the adoption of environmental policies that are supported with legal determinations through the adaptation of Ukrainian water legislation to the best examples in EU countries. The Model " PEP" does not formalize numerical values, but it compares management with general criteria:

$$\text{QQP} \to \text{opt}_{\text{c,q,p}} = 1, \quad \text{WUCR} \to \min_{Q_c, Q_r, Q_l}, \quad \text{EEES} \to \max Q_\Delta / W_\Delta, \quad (2)$$

where Q_Δ, W_Δ - are not zero water and electricity consumption accordingly min, EEES - environmental and energy efficiency systems.

Hence, considering accepted axiomatics it follows that drinking water is a consumer product that matches quantitatively with water supply load on the environment. Therefore, an important criterion of the effective improvement of ESWD is reduction the "WUCR" with transfer of energy savings which are spent on multiple pumping of billions of cubic meters of water, in other industries.

It follows that the basic ecological principle of "WUCR" is resource consumption reduction (water, electricity, etc.) in all areas, including the implementation Q_i with simultaneous growth of environmental and energy efficiency systems (EEES).

Based on the accepted axiomatics and environmental principle of uncertainty, the implementation of the model in the real world needs the concept of acceptable environmental risk (AR) in the drinking water supply of cities to be spread (*Belogurov and Vasylenko, 1980; Vasyljev and Yeremenko, 1980; Yeremenko, 2000; Pryaginskaya, et al. 2002; Petrosov et al., 2003; Vasylenko et al., 2003; Vasylenko and Ya, 2004; Vasylenko, 2006, 2005a, 2005b; 2009*)*:* a) an environmental risk caused by activity in the water supply field, it should not exceed the AR; b) the cost of maintaining AR should correlate with the income received from the water sale; c) the activity of water supply that causes a risk greater than AR is unacceptable, regardless obtained benefits (*Kachynsky, 2001; Mokryy, 2003; Denczew, 2005; Loucks, 2005; Goncharuk et al., 2006; Gomelya, 2007; Vasylenko, 2009; Dunbar, 2011; Wickham, 2011*).

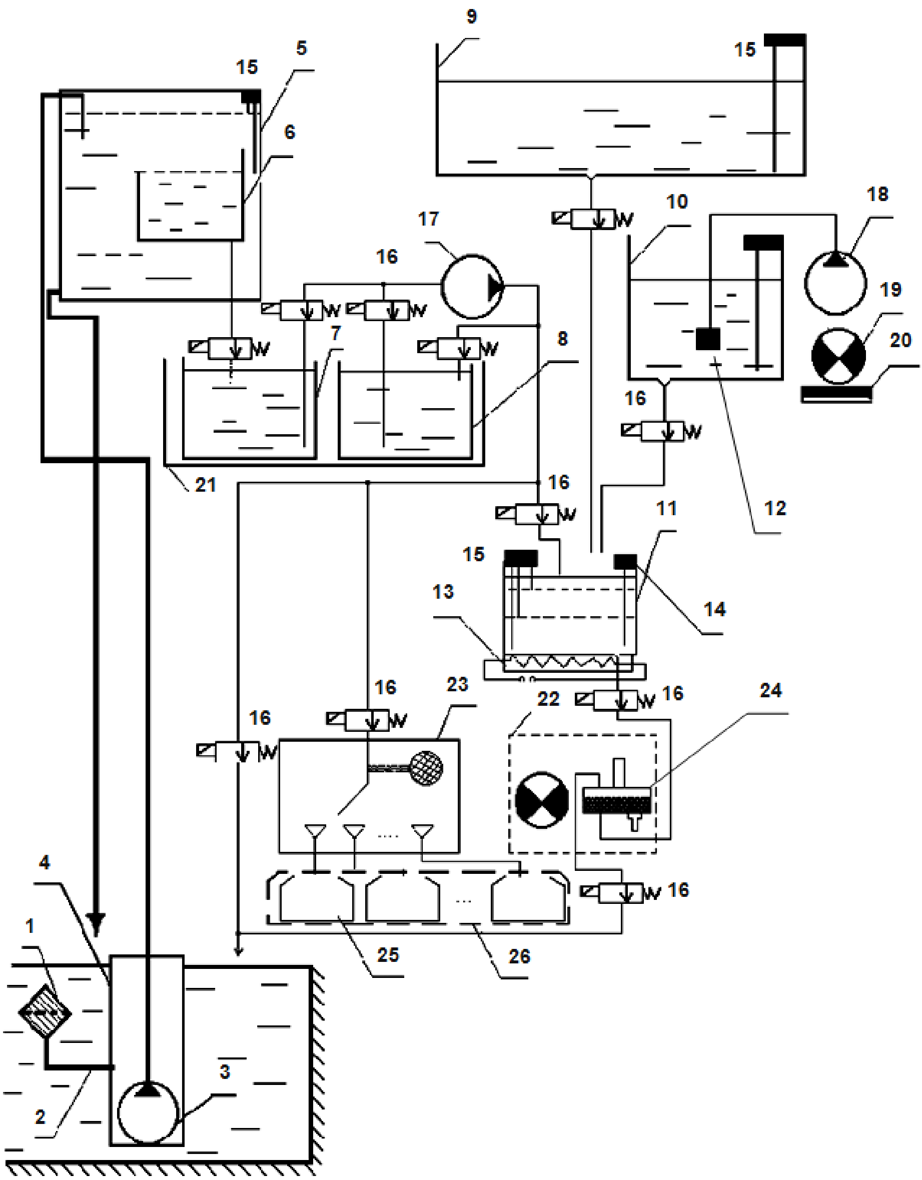

Fig. 3. Functional-hydraulic diagram of automatical post

Therefore according to theoretical propositions of environmental safety for more reliable detection of water pollution was developed an early warning system of deteriorating water quality with automatic post of continuous monitoring of ecological status of surface waters by reaction Biotest object - the culture of green microalgae Scenedesmus or Chlorella (Fig. 3). Water toxicity T is determined by technical means of control gas exchange processes algae outcomes of functional parameters - activity of photosynthesis and respiration. They are determined by silver-platinum sensor 24 to changes in the suspension of dissolved oxygen in the experimental (E) and control (C) samples by the formula

$$T = (1 - \Delta E / \Delta C) \quad 100\% \qquad (3)$$

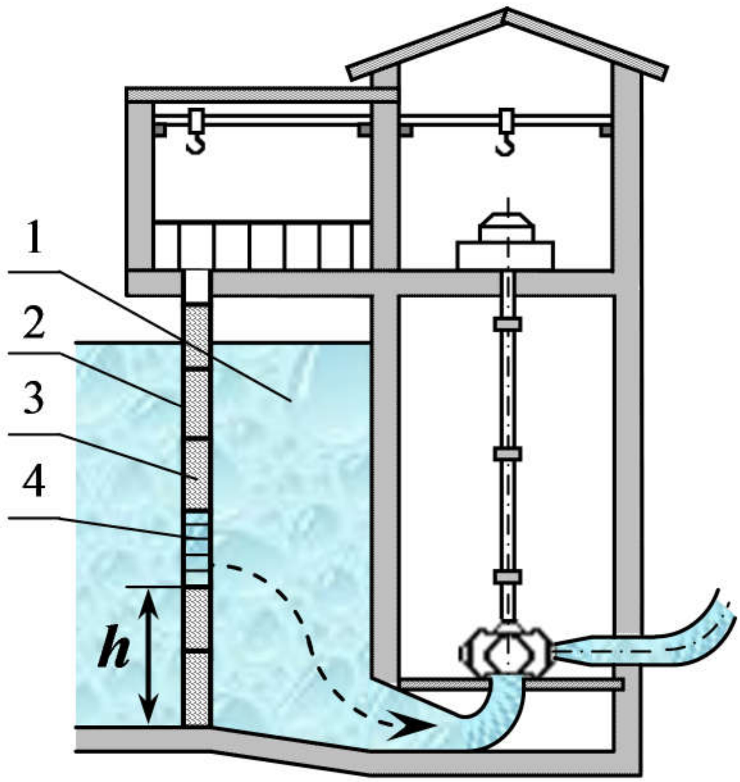

Fig. 4. Intake scheme: 1 – forebay, 2 – grooves, 3 – gates, intake frame with bars

Functionally, the post consists of blocks : water selection and water supply (1–4), preparation (5–8, 17) and storing (21, 25, 26) of samples, seaweed cultivator (10, 12, 18–20), measuring system (9–14 22–24), management and switching (15, 16), display and record of the measurement results, warning and alarm.

Post technical capabilities allow you to connect to a regional system of ecological monitoring. Based on research of natural water composition and experimental measurements of their toxicity, recommended for drinking water set allowable threshold T_m = 40%.

Typical operating conditions intakes proved the presence of environmental risks of water, depending on the vertical stratification of water quality in the reservoir which is seasonal. In order to reduce them, based on ecological principles and system integrators patterns, created a form of environmental safety of water supply, in the form of multi-selective water withdrawal environmental orientation (Fig. 4) It helps to improve the composition and properties of drinking water and return water to minimize the dumping of sewage treatment plants. A cursory solve resource problems of reducing the cost of reagents and electricity consumption for water pumping.

Structurally, gear differs with using the resettable intake frame 4 with protective bars or grids that installed in grooves 2 on the calculated distance h from the forebay bottom 1 with the least water pollution, and the rest of the overlapping area of the vertical section forebay gates 3.

Increasing technological impacts conditions, the necessity of improving the management of water supply and water purification at risk and uncertainty conditions which is a distinctive feature of ecological safety. Common problems of water security include exhaustion and degradation of water objects; ecological condition of surface and underground sources of drinking water; high energy consumption of water supply systems; high water consumption of manufacturing processes; depreciation of fixed assets, deterioration of technical conditions and high accident rate of engineering communications of water economy; increased risk of industrial accidents; potential threat of complications of sanitary and epidemiological situation in certain areas.

Thus, it is necessary to find new approaches to ensure the environmental safety of water supply and drainage in the cities, which include: the development of methodology for studying the ecological security of water supply and water purification; renovation of engineering communications of water supply and sanitation; informatization, robotized monitoring and development of adequate forms of water supply and purification system management.

References

1. Belogurov V.P., Vasylenko S.L.: Статистические модели процессов изменения качества воды в водотоках. *Management of water quality: Coll. Science. works. Harkiv: VNIIVO*, 61–69, 1980,
2. Denczew S.: Zarządzanie systemem zaopatrzenia w wodę jako elementem infrastruktury krytycznej. *Ochrona środowiska*, 4, 69–72, 2005.
3. Dunbar M. J., Acreman V.C.: Applied hydro-ecological science for the twenty-first century. *IAHS Publ*. 266, 1–17, 2011.
4. Gomelya M.D.: Очисні споруди. Основи проектування: навчальний посібник (ed. Gomelya M.D., Krysenko T.V., Dejkun I.M. –К). Ukrainian National Technical University "Kyiv Polytechnic Institute", 2007.
5. Goncharuk V.V., Klymenko N.A., Savchina L.A: Современные проблемы технологи підготовки питьевой воды. *Химия и технология воды.* Т. 28 (1), 3–95, 2006.
6. Kachynsky A.B.: Екологічна безпека України: системний аналіз перспектив покращення. *NISD,* 5. 2001.
7. Loucks D. et al.: Water resources systems planning and management: an introduction to methods, models and applications. Paris: UNESCO, 2005.
8. Mokryy V.I.: Курсове проектування міських інженерних мереж. Methodical manual. UkrLDLU, 2003.
9. Petrosov V. A., Vasylenko S.L., Krasovskiy G. Ya.: Информационное обеспечение питьевого водоснабжения из поверхностных источников на основе ГИС-технологий. *Municipal services cities: Coll. Science. works – К.: Technika*, 53, 15–20, 2003.
10. Petrosov V.A., Agadjanov G.K. , Vasylenko S.L, Ya V.: Эколого-экономическая безопасность хозяйственно-питьевого водоснабжения. *Municipal services cities: Coll. Science. Works,* 55– К., 9–19, 2004.
11. Pryaginskaya V.G., Yaroshevskiy D.M., Levit-Gurevich L.K.: Компьютерное моделирование в управлении водными ресурсами. – М.: Физматлит, 2002.
12. Świderska-Bróż M., Wolska M.: Przyczyny zużycia chloru wolnego w systemie dystrybucji wody. *Ochrona środowiska*, 3, 19–24, 2007.
13. Tillman D.E., Larsen T.A., Pahl-Wostl, Gujer W.: Simulating development strategies for water supply systems. *J. Hydroinf.* 7(1), 41–51, 2005.
14. Vasylenko S.L, Ya V.. Cobylyanskiy, Kolotylo V.D., Pavlenko V.F.: Менеджмент эколого-технической безопасности систем питьевого водоснабжения. S*cientific Bulletin of Construction: Coll. Science. Works. HSTUCA– H.,* 28, 54–60, 2004.
15. Vasylenko S.L., Voloshkina O.S., Krasovskiy G.: Ya. Моделі якості води, зумовленої транскордонним переносом забруднюючих речовин у водотоках. *Ekologiya and resources: Coll. Science. works. – К.: UINSR RNBOU*, 5, 98–105, 2003.
16. Vasylenko S.L.: Акиоматика питьевого водоснабжения. In Vasylenko S.L.: *Environment and Resources: Coll. of Science. works*. IPNB, 14, 55–65, 2006.
17. Vasylenko S.L.: Законы водоснабжения как технической системы. Часть 2. Visnyk NTU, ХПІ, 11, 95–98, 2006.

18. Vasylenko S.L., Voloshkina O.S.: Концепція прийнятного ризику в питному водопостачанні міст. *Environmental Safety and Nature Management: Coll. Science. works.* 4. 130–137, 2009.
19. Vasylenko S.L.: Оценочные показатели энергоэффективности систем централизованного водоснабжения. *Integrated technologies and energy efficiency*, 3, 89–94, 2005.
20. Vasylenko S.L.: Экологическая безопасность водоснабжения: концептуальные положения. *The problems of environmental protection and ecological safety Coll. Science. works. Ucr. NDI environmental problems* , 27– H.: Rider, 174–184, 2005.
21. Vasyljev O.F., Yeremenko E.V.: Моделирование трансформации соединений азота для управления качеством воды в водотоках. *Water resources*, 5, 110–117, 1980.
22. Wickham J. D., Wade T.G., Riitters K.H.: An environmental assessment of United States drinking water watersheds. *Landscape Ecology,* 26(5), 605–616, 2011.
23. Yakovlev Y.Y.: Нові питання регіональної переоцінки та охорони підземних вод України як чинник стратегічної безпеки питного водопостачання. *Ecology and Environmental Safety,* 3, 30–37, 2009.
24. Yatsyk A.V., Geneza K.: Environmental safety in Ukraine, 2001.
25. Yeremenko E.V.: Экологические модели разной сложности для прогнозиро-вания качества воды. *The problems of environmental protection and ecological safety Coll. Science. works. UcrNDIEP*, Harkiv, 2000.

Analysis of possibilities to improve hydraulic conditions in selected water distribution system

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Abstract

The aim of this work is to present the possibilities of improving the flow velocity of water in pipes in selected water distribution system. The analysis was based on the hydraulic model prepared using EPANET application.

The water distribution system is supplied with water from two treatment plants. Pipes' length of the tested network is about 87 km. Pipes diameters on the network are in the range 90–200 mm, while the connections 25–63 mm.

Numerical simulations for the real conditions of the network showed the presence of a very low water flow velocity (below 0.5 m/s) in the most pipes. The low value of flow rate at the hour of maximum water consumption also causes an increase of the retention time of water in the network which may result in secondary pollution of water.

In this work, several simulation were performed for different variants of the numerical model.

The increase of flow velocity in the pipes were achieved by closing appropriate valves, adding new pipelines and changing existing piping diameters, as well as through the implementation of cooperation of both pumping stations.

Suggested solutions can also improve water quality parameters, as well as increase the reliability of the entire water distribution network.

Keywords

numerical model, water distribution system, hydraulic conditions

1 *Introduction*

The basic task of any water supply system is to provide customers with the water in an appropriate amount, pressure, and quality. Changes in water demand observed in recent 30 years result in network hydraulic changes with respect to the design intent, which entails a number of consequences including pressure drops, formation of stagnation zones, failure of the system in terms of efficiency as well as low water flow velocities. This means that the network infrastructure management is a complex process, and both the extension and modernization of water supply system should be based on the analysis of the causes and expected results of introduced changes. Complexity of the systems results in the fact that it is often difficult to conduct such an analysis using traditional methods and it is necessary to support the whole process with available geographical information systems as GIS (Geographical Information System) and numerical modeling of network operation (*Knapik, 2010; Kotowski et al., 2010; Kruszyński, 2011; Burszta-Adamiak et al., 2013; Studziński and Kobylarz, 2014*). Numerical models are a useful tool in managing the water supply network. They allow the assessment of hydraulic parameters of flow, selection pipelines requiring flushing, or analysis of qualitative parameters of flowing water. The basic problem connected with model implementation is to collect a sufficient number of data about structure and topology of analyzed water supply system and obtaining the data needed to model calibration and verification (*Denczew and Królikowski, 2003; Pawlak and Kotowski, 2005; Siwoń, 2005; Kwietniewski ed., 2007; Grzenda, 2009; Jiang et al., 2012*).

One of the most commonly used utility programs allowing for numerical simulation of water distribution system operation is EPANET 2.0 developed by Water Supply and Water Resources Division of the U.S. Environmental Agency (*Bonetyński et al., 2005*). This program is based on the finite elements method using Saint-Venant, Colebrook-White's, and Darcy-Weisbach's equations (*http://www.epa.gov/ORD/NRMRL/wswrd/epanet.html*).

It also allows for conducting both hydraulic calculation of water distribution systems and evaluation of the quality of flowing water. The starting point for calculations is network graph and data describing its particular elements (*Rossmann, 2000; Bonetyński et al., 2007*).

Aim of the paper is to investigate accuracy of the selected water distribution system and variant analysis of the possibilities to improve its functioning. The analyses were conducted using hydraulic model developed in Epanet 2.0. There were conducted 7 different simulation calculations, however, this paper includes results for the three selected calculations: simulation of real conditions, simulation of work operation after correcting diameters and including new segments in the model, as well as simulation of the network supplied by the pumping stations (P1 and P2) from both sides.

2 *Materials and Methods*

2.1. Object of the study

The analyses of hydraulic conditions were conducted for the selected existing municipal water distribution system. Total length of the analyzed network is about 87 km including 47 km of connections. The oldest sections of the network were built about the year 2000 and they are made of polyvinyl chloride (PVC) pipes, newer are mainly polyethylene (PE) pipes. Diameters of the network pipes are between 90–200 mm, however connections are between 25–63 mm. The municipal water distribution system was built in mixed system – ring-shaped and distributing, and it is supplied with water from two water treatment plants (WTP). These plants are connected with each other with pipes built-in ring-shaped, on which there are two closed valves. That is why, pumping stations P1 and P2 do not cooperate, and areas supplied with the water by the particular WTP do not have common zones.

Both WTP alternately exploit totally seven wells with depths ranging between 14.00–22.50 m. In 2014, 254192 m^3 of water has been treated and 252035 m^3 has been given into network.

2.2. Numerical model

Hydraulic model of water supply system was developed using Epanet 2.0. Created model comprised 655 segments and 641 nodes. The following physical parameters have been introduced into the model: pipes' lengths, diameters, roughness, and nodes' ordinates. Moreover, hydraulic parameters have been also introduced, among others the value of calculating water demand. Pressure losses were calculated using Darcy-Weisbach's formula. Assumed time step was equal 1h and whole simulation lasted respectively:

24h for the analysis of hydraulic conditions in the system,

480 h for the analysis of water age in the network.

The scheme of water supply system is presented in Fig. 1.

Due to the lack of appropriate measurements, roughness coefficient k equal 0.8 mm is assigned to the pipeline made of plastic and built between 1998–2000, however in the case of polyethylene one used less than 15 years, this coefficient is equal 0,1 mm (*Sharp and Walski, 1988*).

Calculating water demand defined on the basis of real readings of home water meters are included in the range between 0.006–0.250 dm^3/s. Water consumption per day standard changes have been determined on the basis of the reading of the main water meter located in WTP.

Fig. 1. Scheme of the system with characteristic nodes and pipes

3 Results and Discussion

3.1. Real conditions of network operation

Simulations based on the created hydraulic model allows for defining water flow velocity in the pipes of the analyzed water distribution network for each hour, day, as well as pressure changes and water age in the network nodes.

In order to present changeability of pressure and velocity distribution during the day, five characteristic nodes and the same number of sections (curves) have been selected. The above elements have been chosen taking into account their distance from the pumping station, range of daily changes of hydraulic parameters, and the fact that they should comprise entire network with their range, that is their being representative for the analyzed water supply system. As characteristic curves, the following sections have been chosen: R44, R224, R359, R482 and R660. In order to present daily change of pressure in the network, nodes W142, H220, W232, H526 and H651 have been selected. Figure 1 presents location of the selected pipes and characteristic nodes.

Figure 2–4 present the following graphs: 1) water flow velocity change, 2) pressure change, and 3) water age in the selected (characteristic) pipes and nodes.

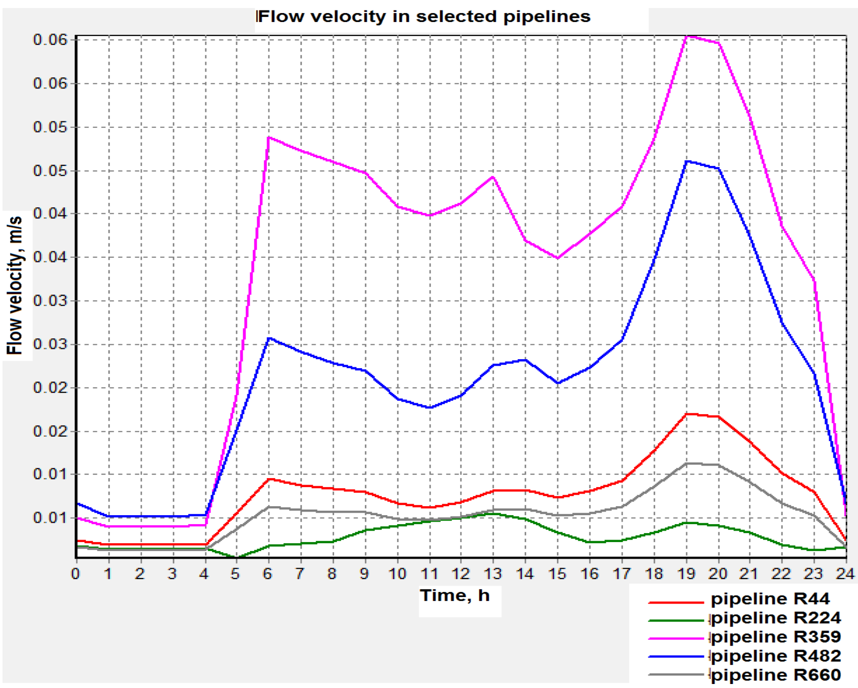


Fig. 2. Change of water flow velocity in selected pipelines

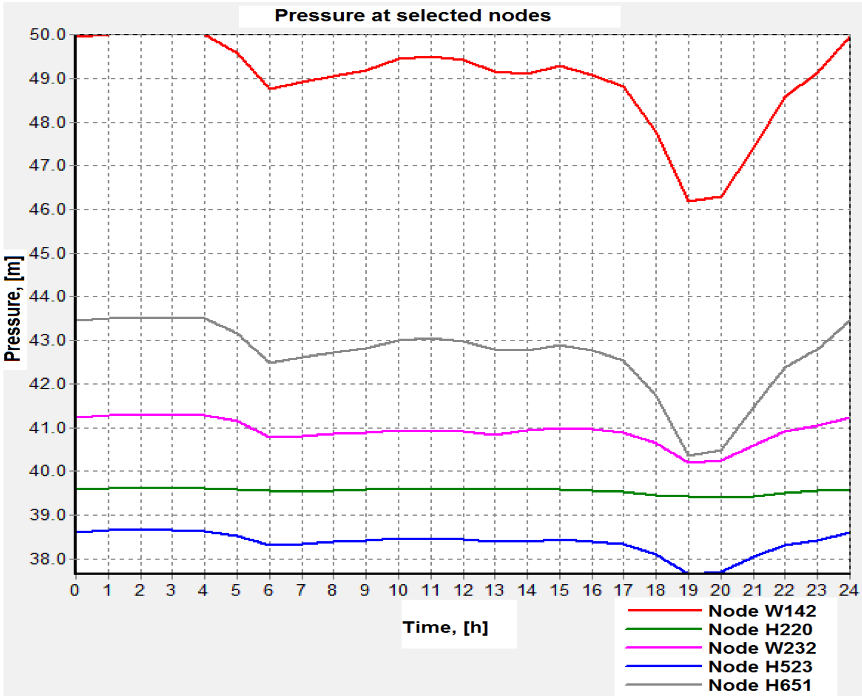


Fig. 3. Change of pressure et selected nodes

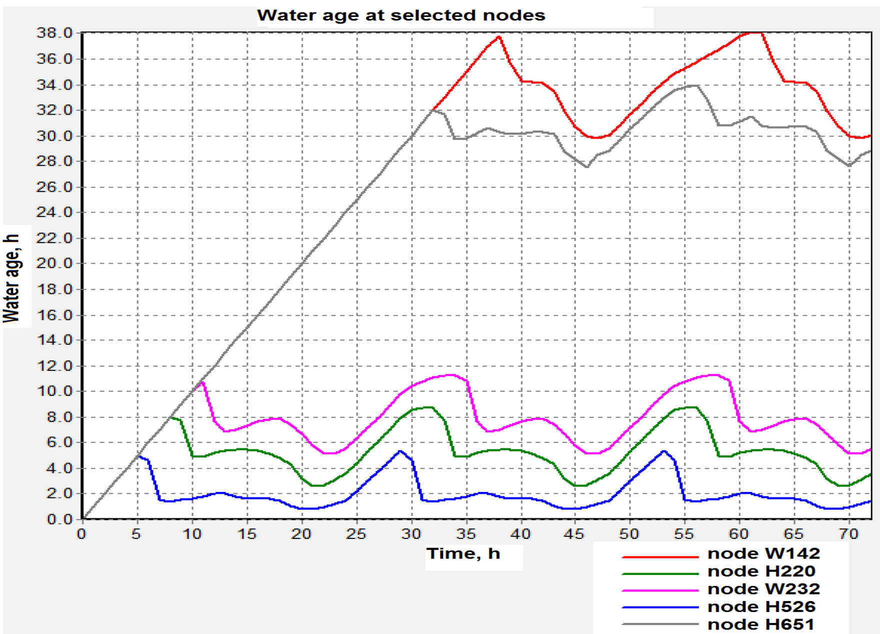


Fig. 4. Change of water age et selected nodes

Table 1 presents the results of simulation calculations of water flow velocity and pressure in the pipes at an hour of maximum water consumption (7 p.m.).

Table 1. Water flow velocity and pressure in the selected pipes and nodes.

Pipe	Velocity [m/s]	Nodes	Pressure [mH_2O]
R44	0.02	W142	46.19
R224	0.01	H220	39.42
R359	0.06	W232	40.19
R482	0.05	H526	37.65
R660	0.01	H651	40.36

On the basis of the obtained results of simulation calculations, it was found that in the analyzed network very low water flow velocities occur. In the hour of maximum water consumption (7 p.m.), the velocities higher than minimum value (v_{min}=0.5 m/s) have been achieved in the pipes connected with the pumping station P2 (*Roman ed., 1991*). In the characteristic pipelines selected for the analyzes of the network operation parameters, water flow velocity is included in the range between 0.01 to 0.06 m/s.

Simulation research revealed that daily pressure changes in the network are small.

The difference between the minimum (46.19 m H_2O) and maximum (50.01 m H_2O) pressure in the lowest node (W 142) and at the same time the most sensitive to changes, does not exceed 4 mH_2O. However, in the highest point of the network (H526) at 7 p.m. it achieves 37.65 mH_2O. The lowest value (36.21 mH_2O) was noticed in the node H588. Conducted calculations obtained that the pressure does not decrease below the required level (20.00 mH_2O) and does not increase over the maximum value (60.00 mH_2O) in any node of the network (*Dz.U. 2009, Nr 124, poz. 1030*). Moreover in any point of the network daily change of pressure level does not exceed 10.00 mH_2O. It results mainly from the applied pressure stabilizing system regulating pump revolutions with respect to the level of consumption.

The analysis of water age indicates that the maximum time of water flow from WTP to the furthest connections equals form 63 to 460 hours (19 days).

Unfavorable conditions of the network operation that has been observed revealed the necessity to search for solutions contributing to the increase of water flow velocity in the pipes.

3.2. Analysis of possibilities to improve hydraulic conditions

Further simulation research included calculations conducted for the model of network with changed diameters of the selected pipes, and added new segments (variant II) as well as in the conditions of supplying the network form two pumping stations P1 and P2 (variant III).

Figure 5 presents model of the network with introduced changes (added segments and changed diameters) and additionally opened/closed valves in order to allow for supplying the network from both sides.

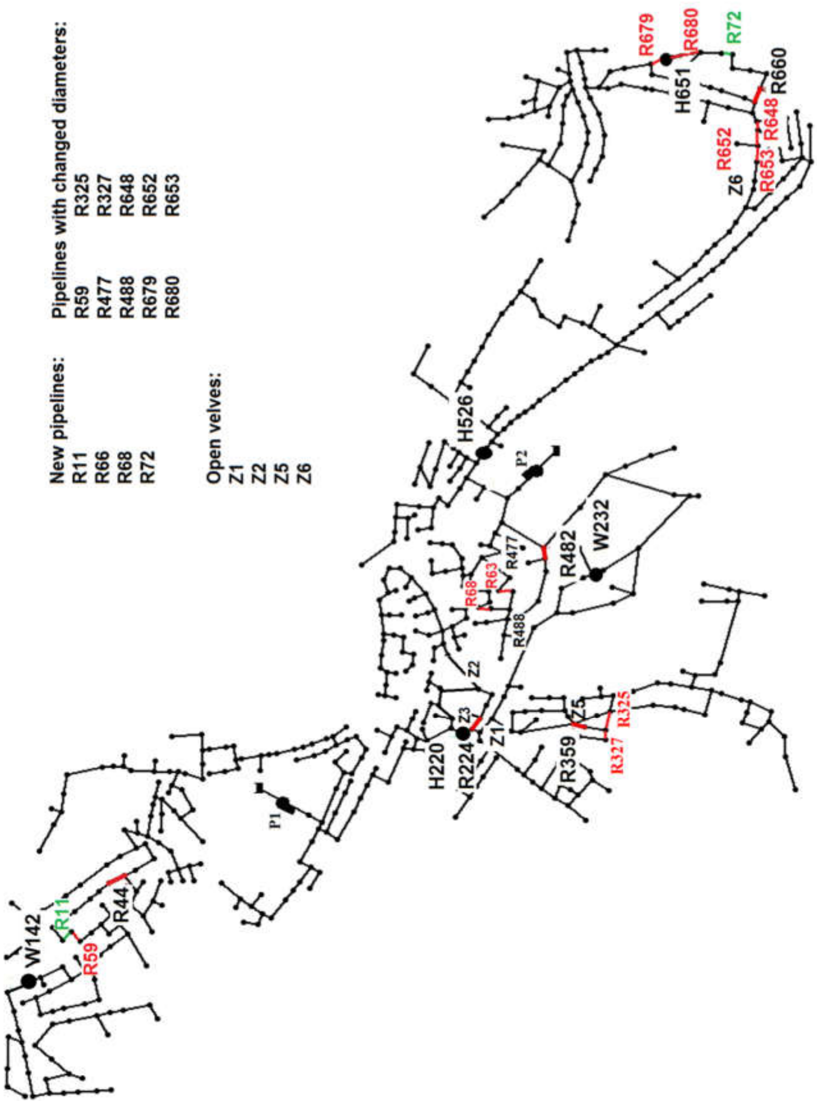


Fig. 5. Model of the network with introduced changes

Table 2 presents the results of simulation calculations of water flow velocities in the pipes obtained for II and III variant at an hour of maximum water consumption (7 p.m.).

Table 3 presents the results of simulation calculations of pressure level at the nodes obtained for II and III variant at an hour of maximum water consumption (7 p.m.).

Tab. 2. Water flow velocity in the pipes

Pipes	**Water flow velocity [m/s]**	
	Variant II	**Variant III**
R44	0.09	0.09
R224	0.04	0.07
R359	0.06	0.06
R482	0.06	0.07
R660	0.05	0.05

Tab. 3. Pressure level at the selected nodes

Nodes	**Pressure [mH_2O]**	
	Variant II	**Variant III**
W142	46.35	48.48
H220	39.41	41.15
W232	40.18	40.77
H526	37.65	37.89
H651	40.38	40.62

Figures 6–8 present the following graphs: 1) changes of the water flow velocities, 2) pressure changes, 3) change of water age in the selected (characteristic) pipes and nodes obtained for II and III variant of calculations.

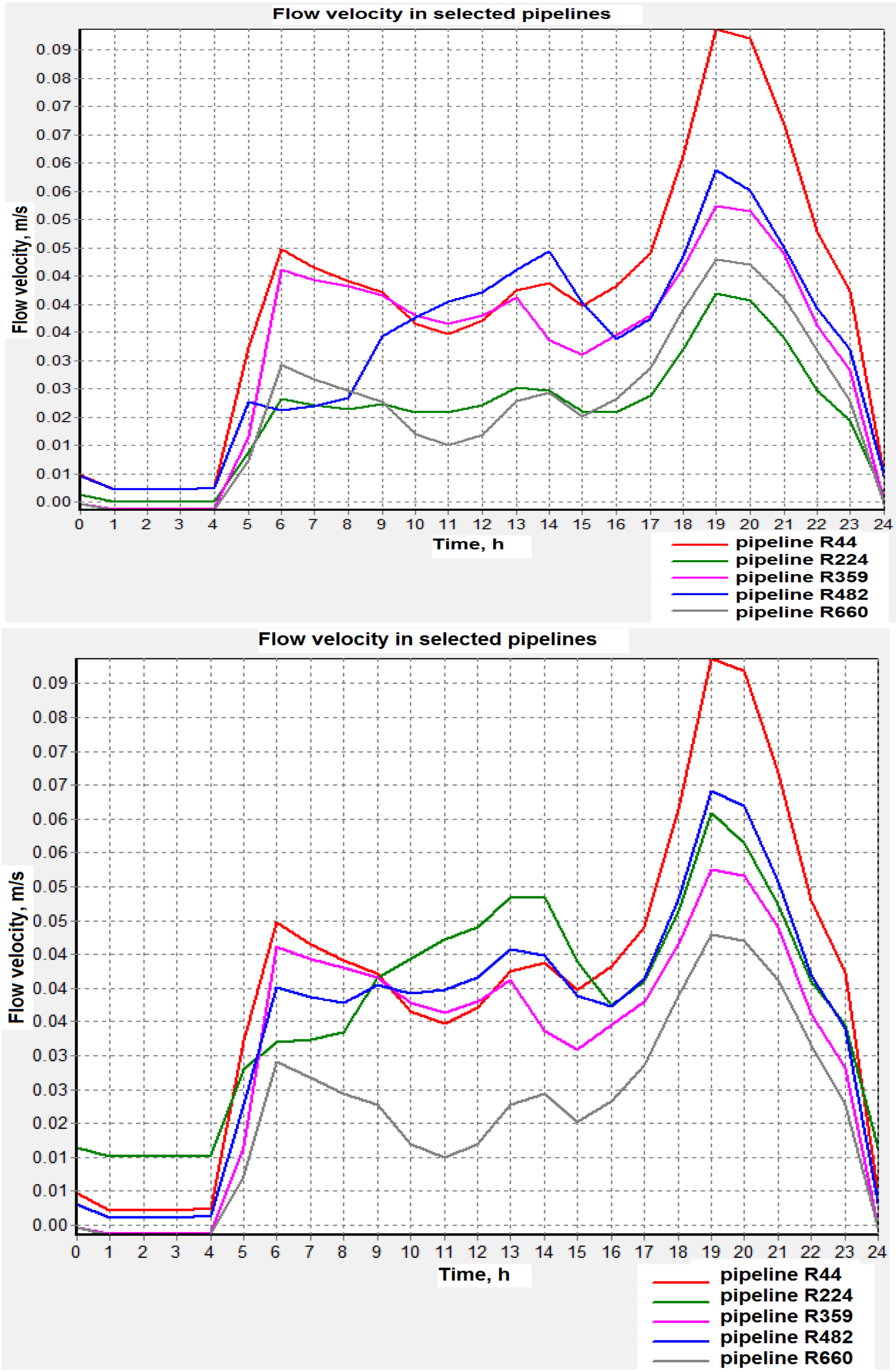
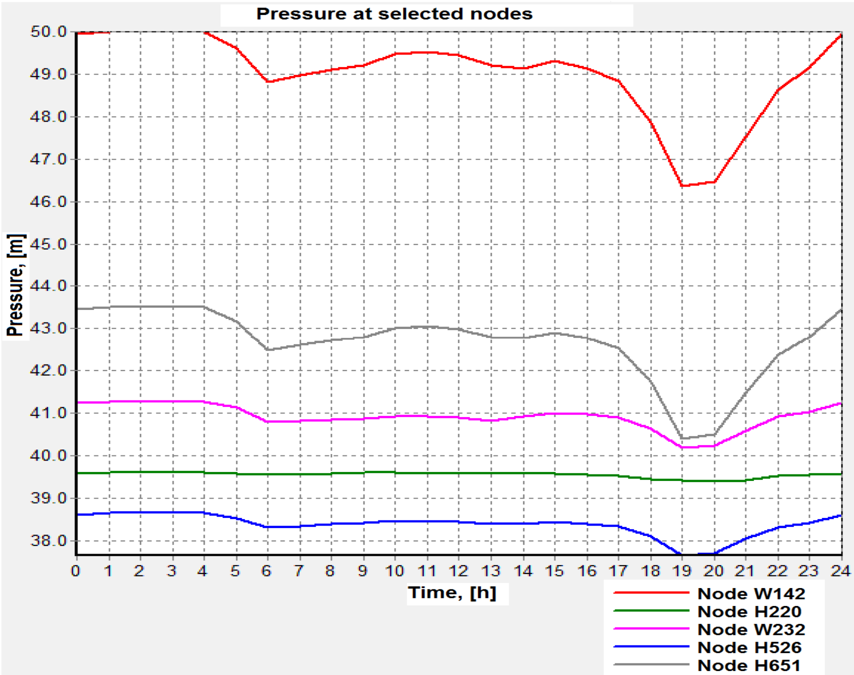


Fig. 6. Graph of water flow velocity changed in the characteristic pipes – II and III variant



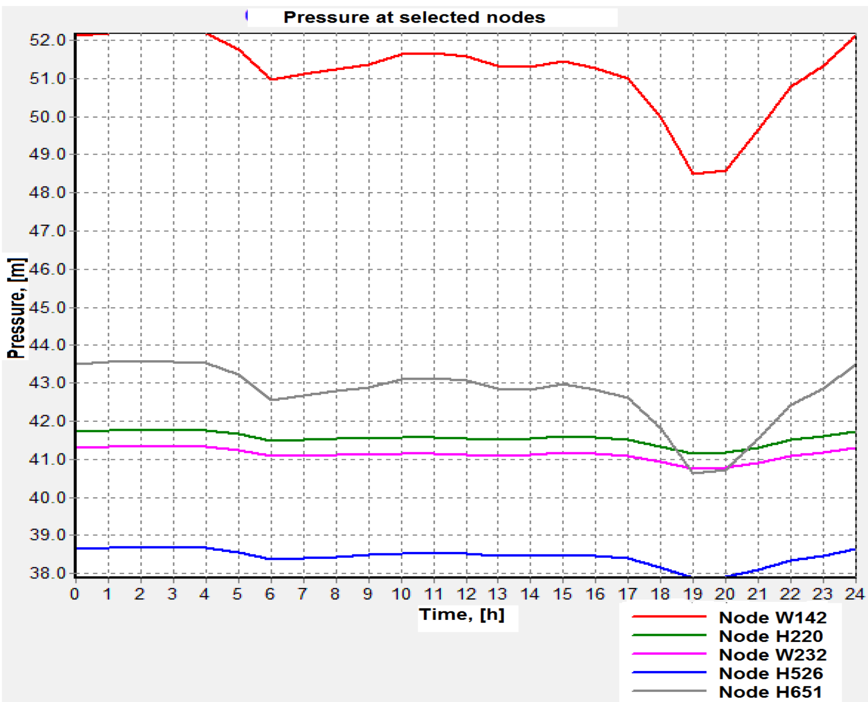
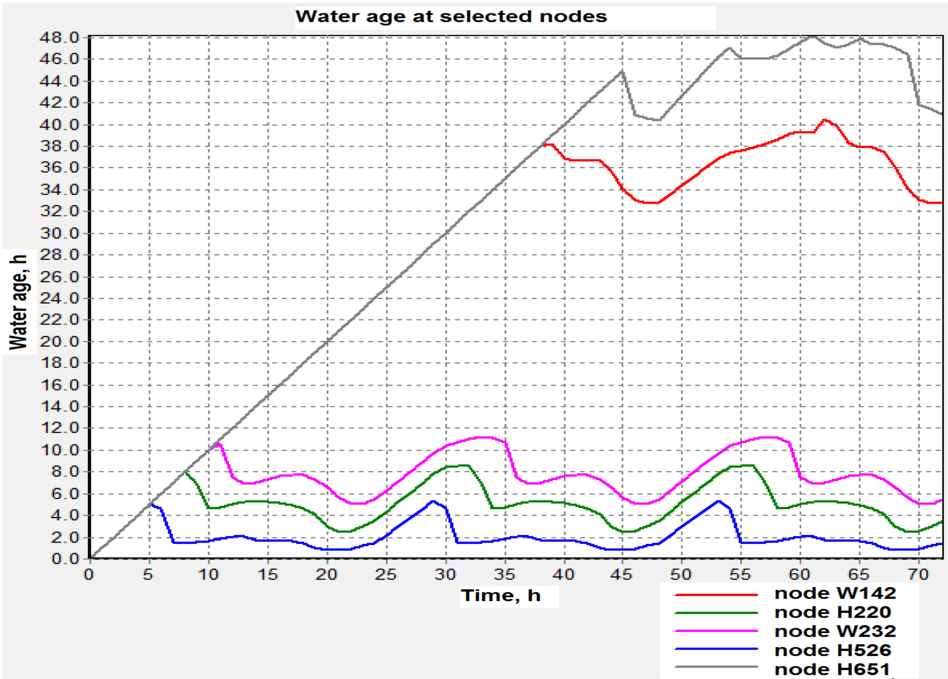


Fig. 7. Graph of pressure level changes at the characteristic nodes – II and III variant of calculations



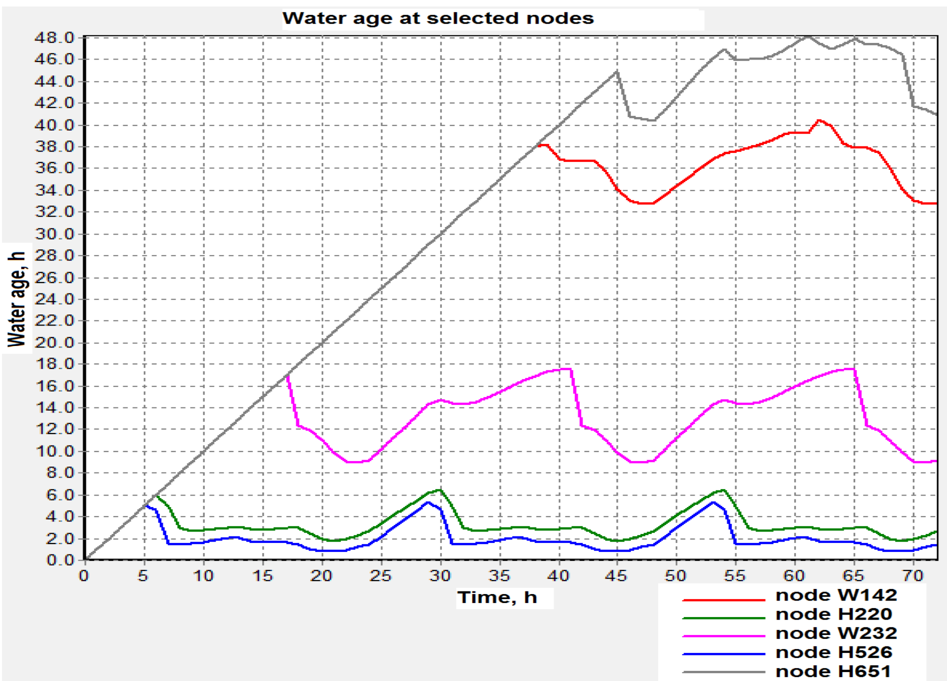


Fig. 8. Water age at the characteristic nodes – II and III variant of calculations

Presented results of simulation calculations reveal that the changes introduced to the network model (changed pipes' diameters, added new segments and changed opening/closing of the selected network valves) influenced the increase of water flow velocity in the pipes. In the characteristic pipes, 3- and 4-fold increase of velocity for II and III variant of calculations, respectively in relation to the values obtained for real conditions (I variant) has been noticed. While the network is supplied from both sides (III variant), velocities are included in the range between 0.07–0.26 m/s, and are higher from those obtained in II variant.

Cooperation of pumping stations P1 and P2 with open valves Z1 and Z2 causes water flow velocity increase, and decreases the difference between the minimum and maximum value of this parameter in the pipes located in the center of the city.

The change of diameters of the selected pipes and creation of new rings by adding new segments do not significantly influenced pressure distribution in the network. In the characteristic nodes increase or decrease of pressure level not exceeding 0.5 mH_2O has been observed. More noticeable changes connected with pressure distribution have been noticed in the model including supplying the network from both sides (III variant). This fact is directly related to the assignment of new standard of pumps impellers rotational speed changes to the pumping station P1. In the lowest node W142, the difference between maximum (52.18 mH_2O) and minimum (48.48 mH_2O) pressure level does not exceed 4 mH_2O. However, at the highest point of the network (H526), at an hour of maximum water consumption, pressure level equals 37.89 mH_2O.

Suggested changes in the model influenced also the water age. In comparison with the real conditions with supplying from both sides, water age decreased averagely of about 4 hours.

4 *Summary and Conclusions*

The analysis of hydraulic parameters dominant in the network in real conditions revealed that water flow velocities in the pipes are very low from 0.01 to 0.06 m/s. This fact influences water retention in the distribution system. The time of water flow from WTP to the furthest connections equals from 63 to 460 hours (19 days). Pressure distribution in the network is balanced and daily hesitations are low, which results mainly from the used stabilizing system. The attempt made in order to improve hydraulic conditions aimed at actions increasing water flow velocity in the network.

Suggested actions, such as correction of selected diameters, addition of new pipes, and opening/closing of selected network valves in order to supply the network from both sides, brought satisfying results. Based on the obtained results of simulation research, it can be stated that:

closing four new circles within the network and changing the diameters of selected segments results in noticeable water flow velocity increase, reduction of the number of zero places in the system, and increasing of its reliability,

during the cooperation of pumping stations P1 and P2, a noticeable increase of water flow velocity and decrease of daily hesitation of pressure level have been observed.

Prepared model of municipal water supply system, after calibration can be used as useful tool for making rational operative decisions connected with exploitation and modernization of existing system.

References

1. Bonetyński K., Kowalski D., Kowalska B., Musz A.: Koncepcja strefowania niewielkiej sieci wodociągowej z wykorzystaniem istniejącego zbiornika wieżowego. Eksploatacja wodociągów i kanalizacji. GIS modelowanie i monitoring w zarządzaniu systemami wodociągowymi i kanalizacyjnymi, Materiały konferencyjne, Warszawa 2007.
2. Bonetyński K., Kowalski D., Musz A.: Zastosowanie programu Epanet 2 PL do badania funkcjonowania sieci wodociągowych. Eksploatacja wodociągów i kanalizacji. GIS modelowanie i monitoring w zarządzaniu systemami wodociągowymi i kanalizacyjnymi, Materiały konferencyjne, Warszawa 2005.
3. Burszta – Adamiak E., Synowiecka J., Przerwa A.: Zastosowanie programu WaterCAD do modelowania i symulacji sieci wodociągowej. Inżynieria i Ochrona Środowiska 16(4), 537–549, 2013.
4. Denczew S., Królikowski A.: Podstawy nowoczesnej eksploatacji układów wodociągowych i kanalizacyjnych. Arkady, Warszawa 2003.
5. Dz.U.2009.124.1030 - Rozporządzenie Ministra Spraw Wewnętrznych i Administracji z dnia 24 lipca 2009 r. w sprawie przeciwpożarowego zaopatrzenia w wodę oraz dróg pożarowych
6. Grzenda M.: Pozyskanie i przetwarzanie danych na potrzeby modelowania pracy sieci. Gaz, Woda i Technika Sanitarna, 6, 16–19, 2009.
7. http://www.epa.gov/ORD/NRMRL/wswrd.epanet.html - data wykorzystania 10.01.2016 r.
8. Jiang B., Zhang F., Gao J., and Zhao H.: Building a Water Distribution Network Hydraulic Model by Using WaterGEMS. ICPTT, 453–461, 2012.
9. Knapik K.: Dynamiczne modele w badaniach sieci wodociągowych. Wydaw. Politechniki Krakowskiej, Kraków 2000.
10. Kotowski A., Pawlak A., Wójtowicz P.: Modelowanie miejskiego systemu zaopatrzenia w wodę na przykładzie osiedla mieszkaniowego Baranówka w Rzeszowie. Ochrona Środowiska 32(2), 43–48, 2010.
11. Kruszyński W.: Modelowanie ciśnienia i przepływów w sieci wodociągowej przy zmniejszającym się zapotrzebowaniu na wodę. Rozprawa doktorska, Białystok 2011.

12. Kwietniewski M. (ed.): Kierunki rozwoju współczesnej eksploatacji obiektów wodociągowych i kanalizacyjnych. W: Wodociągi i Kanalizacja. Monitorowanie sieci wodociągowych i kanalizacyjnych. PZITS, Warszawa 2007.

13. Pawlak A., Kotowski A.: Budowa modeli systemów zaopatrzenia w wodę z wykorzystaniem geograficznych systemów informacji. Mat. konf. „Infrastruktura podziemna miast", Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2005, 282–293.

14. Roman M. (ed.): Poradnik wodociągi i kanalizacja. Podstawy projektowania i eksploatacja. Arkady, Warszawa 1991.

15. Rossman L.A.: EpaNet 2 Users Manual. National Risk Management Research Laboratory. EPA, Cincinnati 2000.

16. Sharp, W. W., Walski T. M.: Predicting internal roughness in water mains, Journal of American Water Works Association 80(11), 34–40, 1988.

17. Siwoń Z.: Symulacyjne modele przepływów w systemach dystrybucji wody – problemy kalibracji i weryfikacji modeli. Mat. konf. „Eksploatacja wodociągów i kanalizacji, GIS modelowanie i monitoring w zarządzaniu systemami wodociągowymi i kanalizacyjnymi", Organizator, Warszawa 2005, 157–184.

18. Studziński A., Kobylarz J.: Jakościowa analiza ryzyka awarii przewodów wodociągowych wodociągu grupowego. Journal Of Civil Engineering, Environment And Architecture JCEEA, t. XXXI, 61 (1/14), 311–321, 2014.

Experimental studies of phytoplankton concentrations in water bodies by using of multispectral images

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Abstract

The aim is to improve performance and reliability of monitoring of nutrient pollution from bioindication by phytoplankton and use of multispectral images. Actuality of the theme caused by the necessity development of new methods of monitoring the state of water bodies based on bioindication by phytoplankton. We improved method of environmental monitoring groundwater multispectral methods and conducted experimental studies of phytoplankton concentrations in water bodies. The paper analyzed the evaluation methods of ecological state of water bodies based on bioindication by phytoplankton and features experimental techniques. Comparison bioassay results wastewater using phytoplankton culture Scenedesmus subspicatus and experimental studies of pollutants specialized laboratory environmental inspection. For identification phytoplankton particles carried compare arrays of multispectral images obtained at characteristic wavelengths of phytoplankton pigments exemplary multispectral imaging using Bayesian classifier on discriminant function based on Mahalanobis distance. Through this increased accuracy of identifying particles of phytoplankton in comparison with classical algologically methods, based on visual comparison of images of phytoplankton particles obtained by the microscope, with exemplary images taken from inventories and determinants, and performance monitoring of the ecological state of water bodies increases by 10 ..20 times.

Keywords

multispectral image, environmental monitoring, phytoplankton, water

1 Introduction

Water resources are a national wealth of each state. Currently, there is a tendency to water pollution by industrial effluents. This disturbs the equilibrium of ecological systems and leads to the loss of their ability to recover. One of the most significant factors affecting the quality of surface waters is their anthropogenic eutrophication. It is the result of human activity and is fast deteriorating water quality due to the receipt of these nutrients and organic substances in quantities far exceeding the usual natural level. At present solve water management problems can not be performed without ensuring the stable functioning of ecosystems of water bodies, without preserving their integrity and stability (*Romanenko et al., 1998; Wright et al., 1993*).

The study aims to improve performance and reliability of control nutrient pollution from bioindication by phytoplankton. Actuality of the theme caused by the necessity development of new methods and means of control of water facilities based on biological indication of phytoplankton, as typical for traditional low value performance and reliability of monitoring.

2 Multispectral monitoring of water pollution based biological indication by phytoplankton

Monitoring of natural aquatic environments may be based by bioindication indexes of phytoplankton. The functional role in ecosystems of phytoplankton - the primary element converting solar energy stream, producer of autochthonous organic matter, an important self-cleaning agent and photosynthetic aeration of water. Phytoplankton is one of the elements of biological classification of ecological status of water bodies according the Water Framework Directive EU 2000 (*2000/60/EC*). The object of control in this study are plankton with particle size to 50 microns. Phytoplankton algae are mostly unicellular, although there are many colonial and filamentous forms, especially in freshwater. In each field reservoir volume concentration of phytoplankton determined by physical, chemical and biological-coenotic conditions (*Dell'Uomo, 1997*). Information on the phytoplankton concentration in water bodies with his great spatial and temporal variation. Volume concentration and ratio of different kinds of phytoplankton depends on the time scale of annual seasonal changes and the depth of the reservoir, its cross section and along the length of the water body.

For identification phytoplankton particles carried compare arrays of multispectral images obtained at characteristic wavelengths of phytoplankton pigments exemplary multispectral imaging using Bayesian classifier on discriminant function based on Mahalanobis distance. Through this increased accuracy of identifying particles of phytoplankton in comparison with classical algologically methods, based on visual comparison of images of phytoplankton particles obtained by the microscope, with exemplary images taken from inventories and determinants, and performance monitoring of the ecological state of water bodies increases by 10..20 times. The main pigment particles present in phytoplankton is chlorophyll a (characteristic wavelengths of 430 nm and 663 nm). Green algae contain chlorophyll b (435 nm, 645 nm). Diatoms and dynofitovyh algae contain chlorophyll c (440 nm, 583 nm, 634 nm). In red algae contain chlorophyll d. In addition to chlorophyll in chloroplasts always available carotenoids content equivalent to estimated beta-carotene (480 nm). Blue-green and red algae contain two types phycobilins (fikotsianyn and fikoeretryn) in different ratios. The proposed method is technically more complex than existing indirect methods of integrated assessment of phytoplankton pigment characteristics for the groups, as can more accurately determine the relationship between certain truck phytoplankton (*Petruk et al., 2012; Petruk et al., 2015a,b*).

The authors developed a structural diagram of the device measuring multispectral television monitoring of the ecological state of water bodies in the parameters of phytoplankton (Fig.1). The device contains a water sample with particles of phytoplankton 1, pump 2, CCD-camera 3, microscope 4, measuring the flow cell 5, capacity 6, database particles of phytoplankton 7, specialized processor 8, clarifier 9, index calculation unit 10, indicator 11.

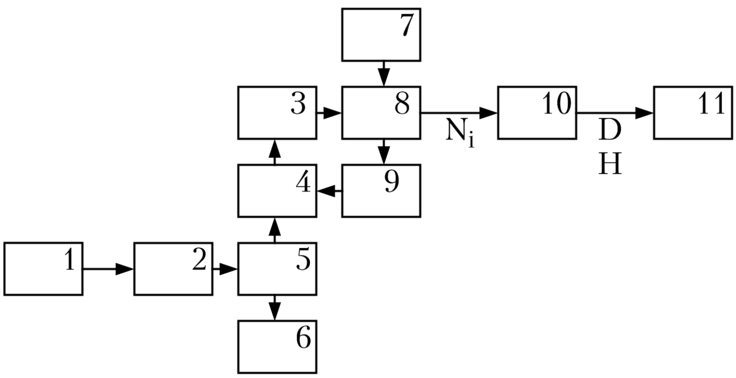

Fig. 1. Block diagram of the device measuring multispectral television monitoring of the ecological state of water bodies in the parameters of phytoplankton

When changing environmental ecosystem water bodies in eutrophication begins with the rapid growth of the number of certain species of phytoplankton, these species begin to dominate in the ecosystem gradually replacing other species of ecosystems. Therefore the relative number of dominant species p_i will grow, which will increase the index of Simpson. In contrast to this in the ecosystem of water body that has good ecological status any species of phytoplankton are not dominant ecosystem is balanced and the relative numbers of different species are small, which reduces the Simpson index. With the deterioration of the ecological state of water body ecosystems, such as anthropogenic pollution because of its most sensitive species of phytoplankton reduce their number and subsequently disappear and are replaced by more resistant to contamination species of phytoplankton, which reduces the index Shannon.

3 Image processing and identification of phytoplankton particles

Is possible identify a certain type of phytoplankton particles based on statistical data on average particle size $\langle \rho \rangle$ or their refractive index $\langle m \rangle$. However, a significant drawback of this approach is the necessity of construction calibration curve to calculate the empirical coefficients also does not take into account the structure and shape of particles because the particles to form complex structures and can not pick up a suspension of artificially created particles whose parameters are known. It is therefore advisable to carry out a direct comparison of multispectral images with images of particles to particles known type, structure, shape and size determined by means of exemplary means of measurements, for example, using an electron microscope. The simplest method of comparison is to compute the difference image (ΔN_{ij}) between elements measured (N_{ij}) and model ($N_{et.ij}$) images

$$\Delta N_{ij} = N_{ij} - N_{et.ij} \tag{1}$$

In terms of the theory of decision a comparison of two dimensional vectors x and y comes to finding the Euclidean distance between them (*Gonzalez et al., 2009*)

$$d(\mathrm{x},\mathrm{y}) = \|\mathrm{x}-\mathrm{y}\| = \|\mathrm{y}-\mathrm{x}\| = \left[(x_1-y_1)^2 + \ldots + (x_n-y_n)^2\right]^{1/2} \tag{2}$$

If the Euclidean distance does not exceed the allowable threshold, the particle corresponds to the same type as the reference image. It should be noted that the size and shape of the particles of a certain type are random variables distributed by the law close to Gaussian, and therefore the threshold should be chosen so as to cover 99.9% of the particles of a certain type, as well as to secure the separation of particles of different types.

The choice of the shortest Euclidean distance is equivalent to calculation of the function

$$d_j(\mathrm{x}) = \mathrm{x}^T \mathrm{m}_j - \frac{1}{2}\mathrm{m}_j^T \mathrm{m}_j \tag{3}$$

where m_j – the average vectors for j class.

Identification of particles to a certain type carried out at the highest value $d_j(\mathrm{x})$. Hypersurface distinguishing between classes ω_i and ω_j in the case of the classifier on a minimum Euclidean distance is determined by the equation (*Gonzalez et al., 2009*)

$$d_{ij}(\mathrm{x}) = d_i(\mathrm{x}) - d_j(\mathrm{x}) = \mathrm{x}^T(\mathrm{m}_i - \mathrm{m}_j) - \frac{1}{2}(\mathrm{m}_i - \mathrm{m}_j)^T(\mathrm{m}_i + \mathrm{m}_j) = 0 \quad (4)$$

It is advisable to use this method of detection of particles, allowing the particles to compare images of different sizes and provide the least value recognition errors.

One such approach is to search for spatial correlation images. In the analysis of the original image $f_1(x,y)$ correlation task is to find the position of the image that best match the reference image $f_2(x,y)$. Because the spatial correlation of images, according to the theorem of correlation reduces to convolution in the frequency domain and search spatial correlation is reduced to multiplication of the transformed images

$$f_1(x,y) \circ f_2(x,y) \Leftrightarrow F_1(u,v) \cdot F_2^*(u,v) \quad (5)$$

where $f_1(x,y) \circ f_2(x,y)$ – spatial correlation, $F_1(u,v) \cdot F_2^*(u,v)$ – a product of transformations images.

To compare images of different dimensions using their processing in the frequency domain using the discrete Fourier transform (DFT), direct DFT $F(u,v) = \mathrm{fft2}(f(x,y))$ is as follows

$$F(u,v) = \sum_{x=0}^{M-1}\sum_{y=0}^{N-1} f(x,y) e^{-j2\pi(ux/M + vy/N)} \quad (6)$$

where $f(x,y)$ – investigated image $M \times N$;

$x = 0,1,2,...,M-1$; $y = 0,1,2,...,N-1$ – spatial coordinates;

$u = 0,1,2,...,M-1$; $v = 0,1,2,...,N-1$ – frequency coordinates.

That is the dimension of matrix is stored in the frequency domain, but its elements are complex numbers. Inverse DFT $f(x,y) = \mathrm{ifft2}(F(u,v))$ is as follows

$$f(x,y) = \frac{1}{MN}\sum_{u=0}^{M-1}\sum_{v=0}^{N-1} F(u,v) e^{-j2\pi(ux/M + vy/N)} \quad (7)$$

Comparing the two images $f_1(x, y)$ and $f_2(x, y)$ using DFT carried out by convolution in the frequency domain:

$$F_1(u,v) = \mathrm{fft2}(f_1(x,y)) \quad (8)$$

$$F_2(u,v) = \text{fft2}(f_2(x,y)) \tag{9}$$

$$F_{con}(u,v) = F_1(u,v) \cdot F_2^*(u,v) \tag{10}$$

$$f_{con}(x,y) = \text{Re}\left(\text{ifft2}\left(F_{con}(u,v)\right)\right) \tag{11}$$

where $F_2^*(u,v)$ – DFT matrix of complex conjugated elements.

When comparing of investigated $f_i(x,y)$ and model $f_s(x,y)$ images define the correlation coefficient between them.

$$k_{corr} = \frac{\frac{1}{M_i N_i}\sum_{x=0}^{M_i-1}\sum_{y=0}^{N_i-1}\left[\text{Re}\left(\text{ifft2}\left(\text{fft2}(f_i(x,y))\cdot\text{fft2}^*(f_s(x,y))\right)\right)\right]}{\frac{1}{M_S N_S}\sum_{x=0}^{M_S-1}\sum_{y=0}^{N_S-1}\left[\text{Re}\left(\text{ifft2}\left(\text{fft2}(f_s(x,y))\cdot\text{fft2}^*(f_s(x,y))\right)\right)\right]} \tag{12}$$

Then conducted comparison image investigated particles x_i with a set of sample images m_j of k types (groups) of particles. The decision to belong to a group of particles performed on the maximum level of the coefficient of correlation. If the resulting value of the maximum correlation coefficient does not exceed a specified threshold value, the particle does not match any of the available types.

On the basis of recognition particle using convolution in the frequency domain using DFT calculate the ratio between the particles of certain groups in total number.

Using spatial correlation images with convolution in the frequency domain with application DFT allows for the detection of particles series of multispectral images and get the ratio of particles of different groups. However, error recognition at the same time is commensurate with the results of visual microscopy.

To increase the probability of control of the concentration of phytoplankton particles should be reduced recognition error of type particles. For this we use the method of detection based on a combination of one particle images obtained at different wavelengths, and comparing them with exemplary multispectral images (Fig. 2).

It should find a set of Euclidean distances between each of the matrices of the family, which will require considerable time for calculation. Another method is to calculate a weighted average of the distance between vectors and families, and the distance is determined by the weight of the matrix, the inverse covariance matrix C_Y model image. This metric is defined Mahalanobis distance (*Gonzalez et al., 2009*)

$$d(\text{m}_\text{Y},\text{m}_\text{X}) = (\text{m}_\text{Y}-\text{m}_\text{X})^T \text{C}_\text{X}^{-1}(\text{m}_\text{Y}-\text{m}_\text{X}) \tag{13}$$

where average families vectors defined as follows:

$$\text{m}_\text{X} = \frac{1}{L}\sum_{l=1}^{L}\text{x}_l \tag{14}$$

$$\mathrm{m_Y} = \frac{1}{L}\sum_{l=1}^{L}\mathrm{y}_l \tag{15}$$

and the covariance matrix of the family model images obtained so

$$\mathrm{C_Y} = \frac{1}{L-1}\sum_{l=1}^{L}(\mathrm{y}_l - \mathrm{m_Y})(\mathrm{y}_l - \mathrm{m_Y})^T \tag{16}$$

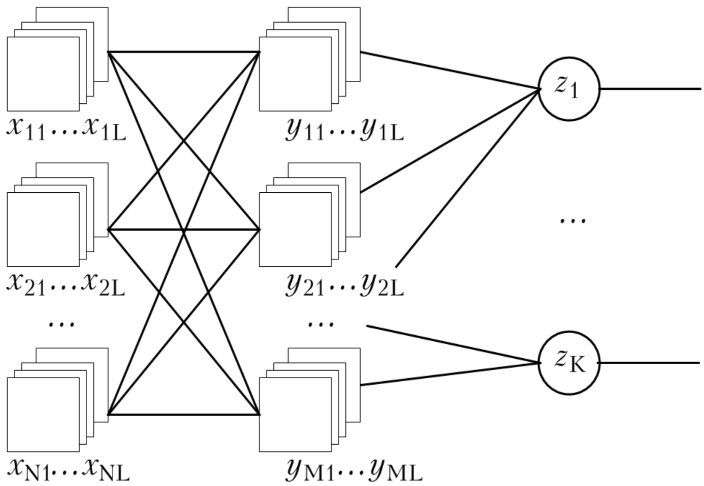

Fig. 2. The scheme of recognition particle based on comparison with exemplary multispectral imaging using Bayesian classifier

We carry out multispectral detection of particles using a statistically optimal classifier Bayesian that has the following crucial function for zero-unit loss function

$$d_j(\mathrm{x}|\omega_j) = p(\mathrm{x}|\omega_j)P(\omega_j) \tag{17}$$

where $j = 1, 2 \ldots K$, $p(\mathbf{x}|\omega_j)$ – density function probability distribu tion for the feature vector class ω_j, $P(\omega_j)$ – class probability of detection ω_j. At a certain feature vector classification process is to calculate all the key rules and to appoint the image class, the decisive rule which gives the number increases.

The probability density function for the feature vector n-dimensional Gaussian random variable have the form:

$$p(\mathrm{m_X}|\omega_j) = \frac{1}{(2\pi)^{n/2}|\mathrm{C}_j|^{1/2}} e^{-\frac{1}{2}\left[(\mathrm{m_X}-\mathrm{m}_j)^T \mathrm{C}_j^{-1}(\mathrm{m_X}-\mathrm{m}_j)\right]} \tag{18}$$

where C_j and m_j – covariance matrix and middle-class vector of family of exemplary pictures; m_X – middle-class vector of family of investigated images; $|C_j|$– determinant of matrix C_j.

Since finding of maximum function $d_j(m_X)$ is equivalent to finding the maximum $\ln(d_j(m_X))$, we can write a function in such a way

$$d'_j(m_X) = \ln\left(p\left(m_X|\omega_j\right)P\left(\omega_j\right)\right) = \ln\left(p\left(m_X|\omega_j\right)\right) + \ln\left(P\left(\omega_j\right)\right) \quad (19)$$

Substituting in (19) a particular function for multivariate Gaussian values, we obtain

$$d'_j(m_X) = \ln\left(P\left(\omega_j\right)\right) - \frac{n}{2}\ln 2\pi - \frac{1}{2}\ln\left|C_j\right| - \frac{1}{2}\left[\left(m_X - m_j\right)^T C_j^{-1}\left(m_X - m_j\right)\right] \quad (20)$$

Discarding is the same for all classes of constant value $\frac{n}{2}\ln 2\pi$, we obtain a decisive function with the Mahalanobis distance in square brackets

$$d''_j(m_X) = \ln\left(P\left(\omega_j\right)\right) - \frac{1}{2}\ln\left|C_j\right| - \frac{1}{2}\left[\left(m_X - m_j\right)^T C_j^{-1}\left(m_X - m_j\right)\right] \quad (21)$$

By increasing the probability of a correct recognition of the particles when using multispectral recognition using the classifier Bayes with decision functions based on Mahalanobis distance in feature space has improved accuracy in determining the ratio of particles phytoplankton groups compared to their recognition on the basis of a correlation processing using a convolution in the frequency domain using DFT.

4 *Experimental analysis of the results of monitoring of phytoplankton*

We carry out an assessment of ecological status of water bodies on the basis of indicators of bioindication by phytoplankton. Selection of phytoplankton samples was carried out in water bodies Vinnitsa using bathometer, as well as with the use of filtration and sedimentation method using a membrane filter. Samples are taken at various locations of the water body at different depths using a bathometer for field study of its hydro-biological parameters such as of phytoplankton concentrations of various species. The study of phytoplankton samples was carried out in vitro in a fixed state (16% formalin solution (2 ml / 200 ml)). The samples are protected from direct sunlight and stored at a constant temperature.

The differences between the spectral absorption characteristics of different groups of algae pigments and different character of the effect of temperature on the relative speed of propagation of phytoplankton leads to a seasonally adjusted number of different groups of algae (Fig. 3).

On the basis of the results of research found seasonal variation changes the relationship between different groups of phytoplankton ponds, caused by natural factors - changes in temperature, solar irradiance, concentration and chemical composition of substances entering the waters with sewage.

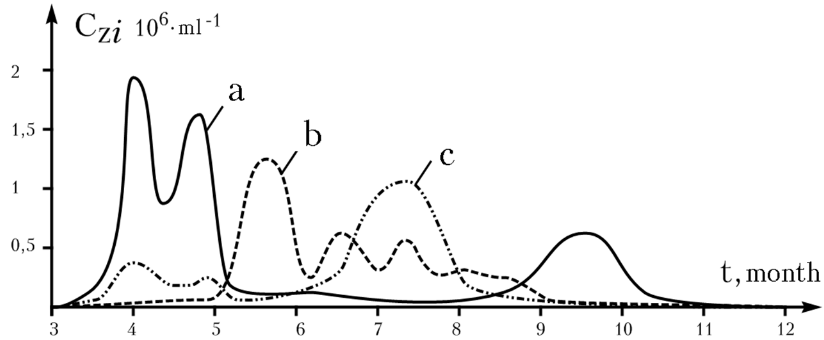

Fig. 3. Seasonal changes in the relations between different groups of phytoplankton:

a – diatoms, b – green, c – blue-green algae

Therefore, it is appropriate to use bioindication indexes to assess the human impact. The degree of indicator species is established using pivot tables and atlases saprobity organisms and monographic treatments of a particular group aquatic organisms (*Barinova et al., 2004, 2005, 2006;Fiorani et al., 2008; Dubelaar et al., 2000; Kopilov et al., 2002; Giakos; 2006; Malkiel et al., 1999*) .

The evaluation of water quality based on the results of bioindication by of phytoplankton carry out such a method. Pollution index is developed based on the method Zelinka-Marwan implemented so (*Dell'Uomo, 1997; Barinova et al., 2004*)

$$S_{EPI} = \frac{\sum_{i=1}^{N} s_i C_{zi} J_i}{\sum_{i=1}^{N} C_{zi} J_i} \qquad (22)$$

where N – number of phytoplankton species that are bioindicators; C_{zi} – the concentration of particles of phytoplankton i -species; s_i , J_i – saprobity a valence and indicator weight species are taken from the reference tables for the species bioindicators.

5 Conclusions

The development of processing industry resulting increase in man-made impact on aquatic ecosystems primarily by increasing the discharge of pollutants from wastewater into local water bodies. Even if new modern technological equipment a number of chemical substances used in manufacturing can get into waste water, such as violations of technological processes or failure of treatment equipment. Therefore the theme of operational control of wastewater toxicity is particularly relevant for environmental inspections.

The paper analyzed the evaluation methods of ecological state of water bodies based on bioindication by phytoplankton and features experimental techniques.

Comparison bioassay results wastewater using phytoplankton culture Scenedesmus subspicatus and experimental studies of pollutants specialized laboratory environmental inspection. We conducted a correlation analysis to identify relationships between concentrations of pollutants and the ratio of the concentrations of phytoplankton in the investigated and the control sample. We found correlations between some parameters of pollutants (concentration of sulfate, ammonium ions, nitrite ions, chloride ions, biochemical oxygen demand) and concentration of phytoplankton, which confirms the possibility of using Scenedesmus subspicatus cultures phytoplankton as bioindicator contamination of waste water. According to the methodology of environmental assessment of surface water quality categories for the relevant water samples are classified as moderately polluted. The results of this study can be used in specialized laboratories for environmental inspections rapid control parameters wastewater.

References

1. Barinova S., Klochenko P., Bilous O., Algae as indicators of ecological state of water bodies: methods and perspectives. *Hydrobiological Journal,* 51(4), 3–23, 2015.
2. Barinova S.S., Anissimova O.V., Nevo E., Jarygin M.M., Wasser S.P.: Diversity and ecology of algae from Nahal Qishon, Northern Israel. *Plant Biosystems,* 138(3), 145–259, 2004.
3. Barinova S.S., Anissimova O.V., Nevo E., Wasser S.P.: Diversity and ecology of phytoplankton and periphyton of the Nahal Oren, Alon Natural Park, Northern Israel. *Algological Studies*, 116, 169–197, 2005.
4. Barinova S.S., Tavassi M., Nevo E.: Algal indicator system of environmental variables in the Hadera River basin, central Israel. *Plant Biosystems,* 140(1), 65–79, 2006.

5. Dell'Uomo A.: Use of algae for monitoring rivers in Italy: current situation and perspectives. Use of algae for monitoring rivers. Agence de l'Eau Artos-Picardie, 17–25, 1997.
6. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities.
7. Dubelaar G. B., Dubelaar R., Jonker R.: Flow cytometry as a tool for the study of phytoplankton. *Sci. Mar.,* 64, 135–156, 2000.
8. Fiorani L., Maltsev V.P., Nekrasov V.M., et. al.: Scanning flow cytometer modified to distinguish phytoplankton cells from their effective size, effective refractive index, depolarization, and fluorescence. *Applied optics*, 47(24), 4405–4412, 2008.
9. Giakos G.C.: Multifusion Multispectral Lightwave Polarimetric Detection Principles and Systems. *IEEE transactions on instrumentation and measurement,* 55(6), 1904–1912, 2006.
10. Gonzalez R.C., Richard E., Woods S.L.: Digital Image Using MATLAB. Second Edition. The MathWorks, Inc. Gatesmark Publishing, 817 p., 2009.
11. Kopilov S.V., Savenko Y.V., Zinkovsky Y. F.: Remote Sensing Monitoring of the Mountain Rivers and Underground. *Proc. International Geoscience and Remote Sensing Symposium,* 132, 2002.
12. Malkiel E., Alquaddoomi O., Katz J.: Measurements of plankton distribution in the ocean using submersible holography. *Measurement Science and Technology.* 10(12), 1142–1152, 1999.
13. Petruk V., Kvaternyuk S., Kozachuk A., Sailarbek S., Gromaszek K.: Multispectral televisional measuring control of the ecological state of waterbodies on the characteristics macrophytes. *Proc. SPIE, Optical Fibers and Their Applications,* 9816, 98161Q, 98161Q-1–98161Q-4, 2015b.
14. Petruk V., Kvaternyuk S., Yasynska V., Kozachuk A., Kotyra A., Romaniuk R.S., Askarova N.: The method of multispectral image processing of phytoplankton processing for environmental control of water pollution. *Proc. SPIE, Optical Fibers and Their Applications*, 9816, 98161N, 98161N-1–98161N-5, 2015a.
15. Petruk V.G., Kvanternyuk S. M, Denysiuk Y. M., Gromaszek K.: The spectral polarimetric control of phytoplankton in photobioreactor of the wastewater treatment. *Proc. SPIE, Optical Fibers and Their Applications*, 8698, 86980H, 86980H-1–86980H-4, 2012.
16. Romanenko V.D., Zhukynskyy V.N., Oksijuk O.P. et al.: Methods of environmental assessment of surface water quality for the respective categories 28 p. 1998.
17. Wright J.F., Furse M.T., Armitage P.D.: RIVPACS – a technique for evaluating the biological quality of rivers in the UK. *European Water Pollution Contro,.* 3 (4), 212–227, 1993.

Biocleaning stormwater of the engineering plant by the immobilized microorganisms and hydrobionts

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Abstract

Biological wastewater treatment is the most ecologically apposite and economically efficient method. For biological treatment of water from toxic substances carrier «VIYA» of ultra-thin and smooth textured chemical fiber was established. The aim of this work was to investigate the efficiency of the combined use of «VIYA» and the root system of water plant (Eichhornia crassipes) covered by immobilized microorganisms and hydrobionts in the cleaning wastewater from nickel ions and oil. In one of the four channels of the STF floating bearing element in the form of a raft with carrier «VIYA» was installed.Then 3–5 plants of Eichhornia were planted in the hole of the bottom of the raft. Developed root system of Eichhorniais is a natural fiber carrier which together with the carrier made of artificial fiber provides effective biological treatment of storm water.

Studies have shown the principle possibility of effective treatment of industrial storm water by microorganisms, hydrobiocenoses and higher water plants attached to floating rafts filled with the submerged carriers «VIYA» with immobilized hydrobionts. Filling the whole channel surface treatment facilities will enhance the cleaning efficiency of water about 5 times. After the immobilization of water organisms of the activated silt in the fibrous carrier «VIYA» during 14 days 39 species were found in the artificial biocenosis vehicle . Biocoenosis periphyton fouling on the fibrous carrier treatment facilities consisted of 40 species of water organisms. Biocoenosis periphyton from fouling root of Eichhornia was represented by 35 species of water organisms. Taxonomic groups were represented by ciliates, rotifers, oligochaetes, copepods, amoebae, testate amoebae, heterotrophic flagellates, nematodes, tardigrades, gastrotrichs, diptera larvae of insects and larvae of water mites. In the bacterial film such species of bacteria as genera Arthrobacter, Achromobacter and Pseudomonas dominated.

Keywords

storm water, petroleum, nickel, carrier «VIYA», floating rafts, activated sludge, bacteria-destructors, hydrobionts, *Eichhornia crassipes*

1 Introduction

The efficiency of the cleaning technology of wastewaters before their return into the basins is one of the key factor that determines the level of pressure on the environment. Bulk of untreated wastewaters increased almost twice since Ukraine became independent (*Roy and Plyatsuk, 2014*).

Steady deterioration of the chemical composition in anthropogenically polluted water and an increase of requirements to the quality of the treated water, at the same time, requires development of new methods of biological water treatment. Biological wastewater treatment is the most ecologically apposite and economically efficient method (*Goncharuk, 2005*).

Different methods of immobilization of microorganisms on the media are widely used in modern biotechnological approaches. There were proposed different medias that can be divided into two categories: 1) regular carriers, mounted (plates, cloths, fabrics, fibers, etc.); 2) irregular carriers –moving in the fluid (sand, activated carbon, various shapes and size of plastic products) (*Zapolsky et al., 2000*).

For biological treatment of water from toxic substances in the Dumanskii Institute of Colloid Chemistry and Water Chemistry of National Academy of Sciences of Ukraine, ultra-thin and smooth textured chemical fiber was developed. This carrier provides a perfect mass transfer and permanent auto regeneration of carrier on which biofilm of microorganisms-destructors exist. Designed fibrous media such as «VIYA» has no equal in the world of the volume of surface area (5000–10000 m^2 per 1 m^2 volume of the treatment structure) and is the most important process parameters (*Gvozdak et al., 2002; Zhurba et al., 2003; Globa and Gvozdyak, 2015*).

It’s known that the wastewater plants are widely used for the treatment of domestic and industrial wastewater (*Vasylyuk, 2008*). Higher water plants regulate quality of the water not only because of their filtration properties, but due to their storage capacity and ability to utilization and transformation of many substances, rapid growth and intensive absorption from the water of almost all biogenic elements and their compounds (*Vasylyuk, 2009*). Tropical plant – *Eichhornia crassipes* – meets all this requirements.

The aim of this work was to investigate the effeciency of the combined use of such medium as «VIYA» and the root system of *Eichhornia* covered by immobilized microorganisms and hydrobionts in the treating the JSC «Motor Sich» wastewater from nickel ions and oil.

2 *Materials and Methods*

Storm water treatment efficiency with application of «VIYA» on floating rafts (*Gvozdak et al., 2002)* and *Eichhornia* was tested on the real treatment facilities of the JSC «Motor Sich»(Zaporozhye). Stormwater treatment facilities (STF) №54 lies outside of the territory of JSC «Motor Sich» in the Shevchenkovskii district, where treated water flows through the living region and falls into a small river Mokra Moskovka.

Treatment process consists of removing mechanical particles (sand traps, mechanical bars), four-section horizontal tanks made of reinforced concrete and filtration via expanded clay aggregate. Through STF№ 54 flows almost 3500 m^3 of storm water per day or 1200000 m^3 per year.

The studied storm water contained 0.21–0.29 mg/dm^3 of the iron ions; 0.07–0,013 mg/dm^3 of the cooper ions; 0.05–0.01 mg/dm^3 of the zinc ions; 0,012–0,043 of the nickel ions; 0,242–16 mg/dm^3 of the oil; 0.7–4.5 mg/$dm^3$of the surfactants and 70–80 mg O_2/dm^3 of COD. The temperature of the wastewater fluctuated during the period of investigation (from November 2013 to November 2014), from 8° to 30°C.

On the base of the previous studies in one of the four channels of the STF№ 54 floating bearing element in the form of a raft (size 1,0*1,5 m) was installed. To the perforated bottom of the raft a fiber carrier was attached in the way, that it was immersed into the water. Primary immobilization of microorganisms and other hydrobionts on the fibrous carrier rafts was performed in the aeration tank of the central treatment facilities Left Bank (DSP-1) of the enterprise «Vodokanal» Zaporozhye, Ukraine during 14 days of autumn 2013. Then, two rafts with immobilized organisms were removed from the aeration tank DSP-1 and placed in the head of one of the channels of STF№ 54 of the JSC «Motor Sich». During exposure of rafts in the aeration tank of the municipal wastewater treatment facilities (autumn 2013) the water temperature at the inlet and outlet was 24 °C and 22 °C respectively, the pH value of water was in the range of 7,51–7,66, the concentration of dissolved oxygen fluctuated between 2,23–2,81 mg O_2/dm^3; indicator BOD_5 was within 11,9–12,4 mg O_2/dm^3, sludge index – 61–76 ml/g, the dose of sludge was from 1.7 g/dm^3 to 2.2 g/dm^3.

Initially, rafts with a fibrous carrier «VIYA» cleaning storm water on their own, and after that since (July 2014) in the hole of the bottom of the raft immersed in water, was planted 3–5 plants of (*Eichhornia crassipes*) (Fig. 1–2).

Fig. 1. Eichhornia crassipes on the water surface of floating rafts
(mid-July 2014)

Fig. 2. *Eichhornia crassipes* on the water surface of floating rafts
(the beginning of August 2014)

Growth dynamics of *Eichhornia* during the summer and autumn was visually observed and photographed (Fig. 3).

Fig. 3. *Eichhornia crassipes* on water surface rafts (3 months vegetation)

Developed root system of higher water plants is a natural fiber carrier which during the study period (July–November 2014), together with the artificial fiber carrier provided the effective biological treatment of storm water from oil and heavy metals because on the root hairs of plants big amount of the bacterial biomass was growing (Fig. 4).

Fig. 4. The root system of *Eichhornia* after 3 months of plant cultivation in the canal of the STF

The content of oil and nickel ions in water from STF № 54 in floating rafts (test) and in the water beyond the pole of the raft (control) were analyzed by atomic absorption method using electrothermal analyzer – spectrophotometer «PerkinElmer», as well as fierce analyzer «Hitachi-180» in a comprehensive sanitary laboratory of the JSC «Motor Sich».

The qualitative composition of the microbiota film on«VIYA» and on the root system *Eichhornia* were studied using the method of direct contact with the surface of the film with the IPA medium in the Petri dishes, and grinding of the biomass on the surface of a glass spatula after that. Microorganisms were cultured for three days in anincubator at 28 ° C. Staining of bacteria was carried by the Gram method *(Holt et al., 1997)*.

Identification of organisms was carried on using determinants and scientific works (*Kahl, 1935; Banina, 1983; Aisa et al., 1984; Warren, 1986; ed. Tsalolihina, 1994, 1995; Alekseeva and Tsalolihina, 2010*) . The number of organisms in biocenosis was determined by method of calibrated drops in triplicate (*Aisa et al., 1984*) Trophic structure of the fauna of the ciliates biocenosis was analyzed on probation by Pratt and Kernsy (*Pratt and Caerns, 1985*) method because one of specific group of ciliates (mixotrophy) was considered as identical to phototrophs. The similarity of species composition of periphyton organisms from the STF was determined by index Sorensen-Czekanowski (*Yu, 1975*).

3 Results and Discussion

Only 2 rafts were mounted at the STF № 54 of the JSC «Motor Sich», their surface was 1.5 m^2, it's 4.4% of the area of the channel. This tiny amount of rafts with immobilized microorganisms-destructors and higher water plants were enough to get marked results of the treatment of waste water from oil and nickel ions (Table 1, 2).

Table 1. The efficiency of purification of polluted wastewater STF № 54 of JSC «Motor Sich» from the oil using the carrier«VIYA» – type

№	Month	control [mg/dm^3]	test [mg/dm^3]	efficiency of «grazing» of oil [%]
1	October	0.171±0.001	0.142±0.002**	16.96±1.56
2	November	0.217±0.001	0.175±0.003**	19.51±1.43
3	December	0.154±0.002	0.099±0.002***	35.5±1.15
4	March	0.301±0.001	0.151±0.006***	49.72±1.07
5	April	0.787±0.001	0.342±0.007***	56.58±1.67

where: * – P<0.05; ** – P <0.01; *** – P <0.001

The effeciency of the sorption of nickel in the beginning of the study was almost equal to efficiency of oil «grazing» but in the spring (April), it exceeded the rate of oil more than 10% (56.58 ± 1,67 and 68.75 ± 0.42% for the oil products and nickel ions, respectively). Perhaps this can be explained, because of volley discharge of effluent into treatment facilities. Also in April, there was observed a significant increase in the concentration of oil in the control sample – 0.787 mg/dm^3 that is almost three times higher than the minimum rate of concentration of oil products for the whole season (0.242 mg/dm^3).

Table 2. Efficiency of purification of wastewater STF №54 of JSC «Motor Sich» from the nickel ions using the carrier«VIYA» – type

№	Month	control [mg/dm^3]	test [mg/dm^3]	efficiency of the sorption of nickel, ions [%]
1	October	0.136±0.001	0.115±0.002*	15.44±1.96
2	November	0.129±0.001	0.102±0.001**	20.67±1.38
3	December	0.141±0.001	0.109±0.002**	22.7±1.42
4	March	0.161±0.002	0.062±0.001***	61.7±0.69
5	April	0.160±0.002	0.050±0.001***	68.75±0.42

where: * – P <0.05; **–P <0.01; ***–P <0.001

Studies shown that among prokaryotic communities Gram-negative bacteria were predominating. Small sticks were the bulk form of bacteria. The observed forms of the colonies generally were round and smooth. Only at the morphotypes «milky white flowers like» was observed the colony gelatinous consistency, with the fringed edge. Most of the colonies were amelanotic. There were separate colonies milky white and beige. Most bacteria belonged to the genus *Arthrobacter, Achromobacter* and *Pseudomonas*.

Biocenosis of the simplest organisms that lives on the fibrous carrier «VIYA» - type during the period of exposure in the aeration tank DSP-1 (Zaporozhye) consisted of 39 species, which belonged to 8 taxonomic groups. The greatest number of species was represented by a group of ciliates (23 species), six species belonged to a group of rotifers. Group Oligochaeta consisted of four species, and nematodes had two forms. Other groups (flagellates, amoeba, tardigrades, larvae of the Diptera) were represented by only one species, of all groups. Regular in the biocenosis on the carrier (during it's exposure into the municipal wastewater facilities) such organisms like infusorian – *Nassula ornata* Ehrenberg, and rotifers – *Lepadella ovalis* (Muller), *Philodina acuticornis* Murray were detected.

During the study of periphyton biocenosis formed on the fibrous carrier like «VIYA»40 species of water organisms belonging to 8 taxonomic groups were found. Among the identified taxonomic groups the largest number of species was in the group of ciliates, where 25 species of ciliates from 9 units and 17 genuses were observed. Rotifers were represented by 5 species, Oligochaeta and testate amoebae by 3 species, both. Other groups (nematodes, copepods, dipterous larvae of insects and mites) included every one species (*Dombrovskii, 2015*).

For fouling biocenosis fibrous medium «VIYA»– type four peaks of the numbers were observed: autumn; November 2013 (an average of 16,000 pieces/ml), and September (15800 pieces/ml); Spring: April 2014 (17600 pieces/ml); and summer: June 2014 (16,000 pieces/ml). The minimal number of organisms, in the ecological community of STF was detected in March (6900 pieces/ml) and August 2014 (7900 pieces/ ml).

The trophic structure of ciliates fauna of biocenosis fibrous media consisted of 4 trophic groups: bacteria detritophages, mixotrophy, non-selective omnivorous organisms and predators. The largest number of ciliates (17) of the studied STF belonged to the bacteria detritophages. This trophic group of ciliates included almost 68% of the all identified composition of ciliates. Predators were represented by 5 species of ciliates and counted about 20% of the total fauna of the ciliates. The smallest part in the trophic structure of ciliates was representatives of non-selective omnivorous organisms (8%, 2 species) and mixotrophy (4%, 1 species). Thus, in the trophic structure of ciliates fauna of biocenosis fibrous medium «VIYA» – type ciliates – consumers of bacteria and detritus dominatedthat it is characteristic for the STF where microorganisms-destructors decompose a large number of organic substances.

During the study of periphyton biocenosis from *Eichhornia* root system of the STF were identified 35 species of water organisms that belong to 9 taxonomic groups. Among the identified taxonomic groups from the studied ecological communities, the largest number of species was characterized as ciliates, where it was found 19 species of ciliates. Rotifers were represented by 5 species, Oligochaeta by 3 species copepods and amoeba by 2 species. Other groups (nematodes gastrotrichs, testate amoebae, heterotrophic flagellates) included everyone species.

The greatest number of species in the periphyton biocenosis from *Eichhornia* roof system was observed in November (18 species). The smallest number was identified in September (8 species). The number of organisms in the biocenosis of *Eichhornia* root system gradually increased from September to November. So, the minimal number of species in the biocenosis of *Eichhornia* roof system was in September (an average of 11,000 pieces/ml), while in October, it grown to 13,000 pieces/ml, and the maximum was found in November (16200 pieces/ml).

A comparative evaluation of the composition of invertebrates faunal from fouling system on STF on the carrier «VIYA» – type and from *Eichhornia* root system was conducted using Sorensen-Czekanowski index. Similarity of organismsfrom fibrous medium such as «VIYA» on treatment facilities DSP-1 (after 2-week exposure) and waste water STF№54 of JSC «Motor Sich» was low (0.2). The degree of similarity in species composition fouling fibrous media such as «VIYA» from treatment facilities DSP-1 and fouling from *Eichhornia* root system at the WWTP of JSC «Motor Sich» was also low (0.3). Probably this is due to the fact that to the treatment facilities at different times different by composition wastewaterfalls. The index of similarity periphyton organisms from the carrier «VIYA» and from *Eichhornia* STF № 54 was also low and reached only 0.35.

Thus, it can be argued that the species composition of the periphyton organisms on the fibrous medium and root system of *Eichhornia* in the same sewage treatment facilities is significantly different. So cooperative using of the fiber carrier «VIYA»-type and the root system of the *Eichhornia* for the cleaning increases the number species of the periphyton (49 species), and this expands food chain of water organisms and makes more efficiently purification of the water from the enterprises. It is necessary by using only 2 rafts. And rafts were placed in the initial part of sewage treatment facilities, where wastewater just entered the channel, and to completely cover the surface of the channel by rafts 45 pices were required. Upon filling the surface of all 4 channels of treatment facilities rafts cleaning efficiency of water should increase significantly.

A positive result of a JSC «Motor Sich» water treatment using a raft with a fibrous carrier and higher water plant – *Eichhornia* led us to calculate efficiency of water treatment incase of full coverage the surface of all channels by rafts and *Eichhornia*. We have calculated the amount of water that is purified in the channel V_1; volume that takes classical loading of expended clay aggregate in one channel (V_2) and the amount of water, which was purified by *Eichhornia* and rafts, provided that they occupy the entire surface of the water channel V_3.

The total volume of wastewater that is purified in the same channel STF№ 54, is equal to:

$$V_1 = 3.0 \cdot 27.6 \cdot 5.0 = 414.0 \text{ m}^3 \quad (1)$$

Based on the known data that the channels studied treatment facilities plant contains of 12 sections loading (concrete block), their volume can be calculated:

$$V_2 = (1.5 \cdot 0.8 \cdot 0.4) \cdot 12 = 5.76 \text{ m}^3 \quad (2)$$

The volume of water that is purified using the raft (in case that they occupy whole surface of the water channel) with a fibrous carrier «VIYA» and *Eichhornia* root system, that are immersed in water to a depth of 20 cm, can also be calculated:

$$V_3 = 0.2 \cdot 27.6 \cdot 5.0 = 27.6 \text{ m}^3 \quad (3)$$

From these calculations, we can see that the volume of «VIYA» and the root system of *Eichhornia* is 4.8 times greater than the volume of 12-cell load, and for complete cleaning of all volume of waste water channel needs15 volumes of fibrous media «VIYA» and the root system of the *Eichhornia*.

The results confirmed the efficiency of the usage of artificial fibers «VIYA»-type on rafts with immobilized microorganisms and hydrobionts for biological cleaning sewage water from the JSC «Motor Sich».

4 Summary and Conclusions

Studies have shown the principle possibility of effective treatment of industrial storm water by microorganisms, hydrobiocenoses and higher water plants attached to the device – floating rafts filled with the submerged carriers «VIYA» with immobilized hydrobionts.

Filling the whole channel surface treatment facilitres would enhance the cleaning efficiency of water about 5 times. After the immobilization of water organisms of the activated silt in the fibrous carrier like such as «VIYA» in the DSP-1 Zaporozhye aeration tank during 14 days in the artificial biocenosis vehicle were found 39 species, which belonged to the 8 taxonomic groups.

Biocoenosis periphyton fouling on the fibrous carrier of JSC «Motor Sich» treatment facilities consisted of 40 species of water organisms. Biocoenosis periphyton from fouling root of *Eichhornia* was represented by 35 species of water organisms that belong to 9 taxonomic groups.

Taxonomic groups were represented by ciliates, rotifers, oligochaetes, copepods, amoebae, testate amoebae, heterotrophic flagellates, nematodes, tardigrades, gastrotrichs, Diptera larvae of insects and larvae of water mites. In the bacterial film such species of bacteria as genera *Arthrobacter, Achromobacter* and *Pseudomonas* dominated.

References

1. Aisa A.A., et al., Kutikova L.A. (ed.): Fauna aeration: satin. Science: Leningrad Office, 1984.
2. Banina N.N.: *Peritricha Sessilida* in activated sludge biocenosis. Protozoology: simple activated sludge. – L. 8, 87–116, 1983.
3. Dombrovskii K.O.: Biocoenosis periphyton fouling him fibrous media at wastewater treatment plant JSC «Motor Sich». *Journal of Zaporizhzhya National Univ.: technologies. Biological sciences.* Zaporizhzhya: Zaporizky natsionalny University Press, (1), 149–163, 2015.
4. Alekseeva V.R., Tsalolihina S.J. (ed.): The determinant of zooplankton and zoobenthos fresh waters of European Russia. – V. 1. Zooplankton, 2010.

5. Goncharuk V.V. (ed.): Environmental aspects of modern technologies protect the aquatic environment – K.: Scientific thought, 2005.
6. Tsalolihina S.Y. (ed.): Key to freshwater invertebrates of Russia and adjacent territories. – V. 1. Lower invertebrates, 1994.
7. Tsalolihina S.Y. (ed.): Key to freshwater invertebrates of Russia and adjacent territories. – V. 2. Crustaceans,1995.
8. Globa L.I., Gvozdyak P.I.: Biological chemical detoxification pathogens in aqueous medium . *Hygiene and sanitation*, 94(1), 46–50, 2015.
9. Gvozdak P.I., Udilova O.F., Manko N., Moltschaniwskyj G.: Biological and physical intensification of waste water detoxification in lagoons. *Waste Stabilization ponds*. 5-th International IWA Conference papers, 2, 651–656, 2002.
10. Holt J., Krieg N. Smith, P., et al.: The determinant of bacteria Bergi. Publishing House «Mir»,– In the 2 V., 1997.
11. Kahl A.: Urtiereoder Protozoa. 1. Wimpertiere oder *Ciliata* (*Infusoria*). 4. *Peritricha* und *Chonotricha*. Die Tierwelt Deutschlands / Ed. F. Dahl. – Jena: G. Fischer, 651–805, 1935.
12. Zhurba M.G., et al.: Water intake, water treatment plantand equipment: studies. Tutorial (Ed. M.G. Zhurba). AST, 2003.
13. Pratt J.R., Caerns J.: Functional Groups in the Protozoa: Roles in Differing Ecosystems. *J. Protozool.* 32 (3), 415–423, 1985.
14. Roy I.O., Plyatsuk L.D.: Evaluation ofecological securityof centralized drinking water supply in Ukraine, *Journal of Engineering Sciences,* 1(1), 7–14, 2014.
15. Vasylyuk T.P.: The effect of biological wastewater treatment method using plant species *Eichhornia crassipes* Martius at different hydraulic loading. *Biotechnology*, 2(1), 99–106, 2009.
16. Vasylyuk T.P.: The use of aquatic species *Eichhornia crassipes* for sewage treatment. *Ecology and Environment Safety*, 4, 63–68, 2008.
17. Warren A.: A revision of the genus *Vorticella* (*Ciliophora: Peritrichida*). Bull. Brit. Mus. Natur. Hist. (Zool), 50(1), 1–57, 1986.
18. Yu O.: Fundamentals of Ecology (Ed. Naumova N.P.), 1975.
19. Zapolsky A.K., Mishkova-Klimenko N.A., Astrelin I.M.: that in. Physical and chemicalbases of technology ofwastewater treatment: Textbook., Libra, 2000.

Multi-criteria decision analysis of selected water supply network's rehabilitation methods

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Abstract

The minimal operation time of new designed water supply network pipelines is 50 years. The necessity of periodical rehabilitation of pipelines is caused by structure changes of their endurance due to actions of numerous external and internal factors. Currently, there are several rehabilitation methods, including both traditional and unconventional methods. Each pipe rehabilitation should be firstly preceded by a comprehensive evaluation of a chosen technology and its financial profitability. One of many project's evaluation tools is a multi-criteria decision analysis.

The paper presents an exemplary multi-criteria decision analysis of a water supply pipeline rehabilitation. The analysed pipeline was a fragment of a water supply system of a small town in Lublin Voivodeship. Two different unconventional rehabilitation methods were analysed: static cracking and horizontal directional drilling. Additionally, a conventional excavation-based method was also evaluated. Each of the rehabilitation variants was analysed by five main criteria, which were respectively weighted. The criteria weights were established in accordance to the most important issues – financial costs (weight: 31%), needed time (25%) and ecological (20%), social (14%) and technical (10%) aspects. Every criterion was further divided into sub-criteria. In accordance to weighted criteria, the general mark of each of examined renovation method was calculated.

As the result of executed analysis, the method of horizontal directional drilling was defined as the most advantageous. That method was evaluated with the highest general mark, but also with the highest mark among four of five main criteria. The executed analysis can be very helpful during the decision process, due to the fact that the selection of a chosen method can be supported with rational reasons.

Keywords

multi-criteria decision analysis, MCDA, trenchless rehabilitation's methods, water supply network rehabilitation

1 Introduction

The minimal operational time of new designed water supply network pipelines is 50 years (*Knapik and Bajer, 2011*). That period is often exceeded, even beyond the technical durability of pipelines (*Dohnalik and Jędrzejewski, 2004*), which is limited and depends on a kind of pipe's material: approx. 50 years for steel pipes and 75–80 for cast iron pipes (*Kwietniewski, 2011*). After exceeding technical durability time, water supply pipes should be rehabilitated – their technical efficiency should be re-established and therefore time of their exploitation will be extended (*Piechurski and Dzikowski, 2012*). The necessity of water supply pipe's renewal is mainly caused by a loss of a proper constructional stability of pipelines, which can contribute to pipes failures (*Kuliczkowski, 2011*). The loss of a proper stability is a natural consequence of pipes ageing (*Bergel, 2013*), but also the effect of many external and internal factors influencing the water supply pipe (*Chwiałkowska, 2012*). The change of constant and variable loads affecting pipeline and varying soil-water conditions are main external factors. Main internal factors are: changes of water pressure in water supply system, occurring water hammer effects and changes of temperature, flow and chemical composition of water. The process of constructional stability loss may be also accelerated by corrosion processes (*Dąbrowska, 2004*), material defects (*Kwietniewski and Leśniewski, 2007*) and the improper water supply network exploitation (*Kusak et al., 2002*). The correct pipelines rehabilitation can cause the decrease of number of failure and their costs, the increase of reliability, the pressure stabilization in water supply network, smaller hydraulic resistance and pressure losses, and the quality increase of water delivered to customers (*Mielcarzewicz, 1997*).

There are several kinds of water supply pipelines rehabilitation methods: repairs, renovations, modernizations and replacements (*Chwiałkowska, 2012*). During repairs, the damaged part of pipe is fixed in accordance to a current technology, while during renovations the used constructive material is being reconstructed. The aim of modernization is to increase the use value of a water supply element because of its improper functioning (*Mielcarzewicz, 1997*), while the replacement of a pipeline means that the initial technical condition of a system is restored by building a new water supply element (*Knapik and Bajer, 2011*). The plurality of factors that limit the technical durability of pipelines causes the necessity of applying the proper technology of rehabilitation in a dependence to technical condition of a pipeline. The very first step to a correct renwal method application is the collection of a technical documentation and the analysis of hydraulic conditions in water supply pipeline (*Piechurski and Dzikowski, 2012*). The construction evaluation of a water supply pipe can be helpful in deciding whether the pipeline should be: a) replaced, b) reconstructed or c) renovated (*Kuliczkowski, 2011*). In addition, probabilistic models of water supply pipelines failure are more and more popular modern tools, used to support the process of selection of a renewal method (*Scholten et al., 2014*).

After choosing the proper rehabilitation method, a technique of its application should be specified. Generally, methods are differentiated as traditional (trench) and unconventional (trenchless) (*Knapik and Bajer, 2011*). The most popular trenchless renovation methods are (*Kuliczkowski et al., 2010*): cement layer spay, epoxy layer spray, relining, splining. The replacement of a pipeline also can be done in a trench or trenchless method. The most popular trenchless replacement methods are (*Knapik and Bajer, 2011*): microtunnelling, horizontal directional drilling and moling. The trenchless replacement processes can be realised with simultaneous removal of an existing pipe or with not – then the existing pipe is left in a ground (*Kuliczkowski et al., 2010*). The dynamic development of a trenchless water supply pipes rehabilitation methods caused that investors are facing the difficult task of choosing the investment realization technology among many possibilities. Therefore, before the realization, every investment project should be evaluated by financial profitability aspects and it should be considered whether the applied technology is the best possible one. Methods of the investment project evaluation are static (no allowance of a varying in time value of a money) and dynamic (including varying in time value of a money) (*Prusak, 2001*). The other method used to evaluate the investment project is a multi-criteria decision analysis (MCDA), which is a tool that can point the best possible variant of an investment, basing on selected weighted criteria (*Figueira et al., 2005*). Evaluations of analysed variants are weighted arithmetic means of partial marks, estimated in accordance to different category weights. The most difficult task in multi-criteria decision analysis is a proper criteria and weight estimation (*Książek, 2011*). The lack of universal criteria set cause the need of an individual approach during multi-criteria decision analysis. Every time, established criteria should include both the technical characterization of an object and the aim of a pursued analysis (*Mucha et al., 2012*).

This paper presents an exemplary multi-criteria decision analysis of selected water supply network's rehabilitation methods.

2 Materials and Methods

The multi-criteria decision analysis of selected water supply network's rehabilitation methods was pursued for a fragment of a water supply network, existing in a small town in Lublin Voivodeship (approx. 4000 inhabitants). Water supply network materials are mainly: asbestos-cement, cast iron and steel (mainly water supply house connections). Pipes diameters are DN40–DN150. The water supply network is characterized by high failure and leakage factors. The analysed fragment of a network was 6336 m long with approx. 850 m house pipes connections.

Due to the localization of water supply pipelines in a street, small diameters of pipes and the technical condition of pipes, three several methods of a renovation were considered: the replacement of a pipe by a static cracking method (variant 1), the building of a new water supply pipeline in a horizontal directional drilling technology (variant 2), and replacement of a pipe in a conventional trench excavation-based method (variant 3). The bad technical condition of an analysed water supply network fragment caused that other methods (cement layer spay, epoxy layer spray, relining, splining) were rejected. In all 3 variants, the analysis included the same pipe material: PE100 RC SDR11.

The method in variant 1 – replacement of a water supply pipe by a static cracking method – means that the new pipeline is built in a place of an old one, with simultaneous destruction of an old pipeline by a cracking head. In this method it is possible to build a new pipeline with the same or bigger diameter in comparison to an existing one. The new water supply pipeline intercepts all functions of an old pipeline – it has a sufficient durability to carry external and internal influencing loads, and ensure a sufficient hydraulic durability. Despite the fact, that static cracking replacement method is a trenchless rehabilitation method, it requires an initial and final excavation for each replaced section. In variant 1, the final excavation was automatically established as the initial excavation for a next section. It is highly recommended, that the renewal process in this method should be firstly preceded by ensuring a substitutional water delivery to customers by a temporary water supply pipes in order to minimise the water supply discontinuity. The building of a new water supply pipeline in a horizontal directional drilling technology is realized in two basic steps: the pilot drilling and the return drilling with simultaneous location of a new pipeline. The horizontal drilling technology requires an adequate safe zone around the building pipeline, in order not to damage an existing underground infrastructure. The rehabilitation by a drilling technology can be done from the surface level or an initial and final excavation can be required. In order to present basic differences between trenchless and trench methods, the analysis included also a conventional method – traditional excavation-based method. In this technology, pipeline is installed in open excavations, what means that fragments of roads are usually periodically closed.

All 3 rehabilitation variants were evaluated by the multi-criteria decision analysis, in accordance to 5 main respectively weighted criteria: technical (weight: 10%), economical (31%), time (25%), ecological (20%) and social (14%). Main and sub-criteria are presented in table 1. The biggest weight was putted to an economical criterion due to the fact that the investment could be sub-financed from European Union resources. Main criteria were further divided into respectively weighted sub-criteria. The technical main criterion was divided into 3 sub-criteria, which included the possibility of a realization of the investment in a selected technology, the possibility of using selected material and included also technical aspects of further exploitation of a pipeline. The economical criterion was analysed in accordance to costs of eventual excavations and drainage of excavations, costs of roadway closing and occupation, costs of a substitute water delivery for technological and consumer purposes, costs of road surface reconstruction and costs of possible investment risk. The time criterion was divided into 3 sub-criteria: preparation, installation and reconstruction time. The economical criterion included following aspects: the risk of groundwater contamination and lowering, fumes and noise increase, and the possible municipal greenery damage. By the social criterion, the life conditions impediments were evaluated – by 3 sub-criteria: excessive noise, roadway occupation difficulties and water supply hindrances. Each sub-criterion was marked from 1 to 5, where 5 was the highest possible mark.

Table 1. Main and sub- criteria with weights and descriptions

No.	Main criterion	Weight [%]	No.	Sub-criterion	Weight [%]	Mark description
1	Technical	10	1.1	realization possibility	50	1 – many contraindications 5 – no contraindications
			1.2	material application	35	
			1.3	operational conditions	15	
2	Economical	31	2.1	excavation, drainage	25	1 – high costs 5 – low costs
			2.2	roadway occupation	25	
			2.3	substitute water supply	20	
			2.4	roadway reconstruction	20	
			2.5	investment risk	10	
3	Time	25	3.1	preparation	30	1 – long time 5 – short time
			3.2	installation	40	
			3.3	roadway reconstruction	30	
4	Ecological	20	4.1	groundwater contamination	30	1 – high risk 5 – low risk
			4.2	groundwater lowering	30	
			4.3	fumes, noise	20	
			4.4	municipal greenery damage	20	
5	Social	14	5.1	excessive noise	30	1 – big impediments 5 – low impediments
			5.2	roadway occupation	40	
			5.3	water supply hindrance	30	

3 Results and Discussion

3.1 Variants evaluation

By technical criterion, firstly the investment realization possibility was analysed. Variant 3 (traditional method) received mark 2.5 due to the existence of many realization contractions. The analysed fragment of a water supply network is located in a narrow street, where is no enough space for excavated ground storage. The other rehabilitation methods (variants 1 and 2) were evaluated with mark 4 – no contractions for investment realization. Every analysed rehabilitation method can be realized with PE100 material, and therefore every variant was marked with the highest possible grade. The application of the same material in every analysed variant means that future exploitation of a water supply pipeline is only a theoretical consideration. It was assumed that in trenchless variants (1 and 2) there is a bigger risk of cracking and scratching of the pipe and therefore these variants were mark as 3 by sub-criterion 1.3. The traditional method was marked with 4.

In the first economical sub-criterion, costs of excavation and its drainage were estimated. The trench method in variant 3 was marked as the one that generates the biggest costs (mark 1), due to the fact that there is a necessity of excavation alongside the whole pipeline. Both trenchless methods were marked with 4, assuming the necessity of realization of initial and final excavation. Costs of roadway occupation were the biggest in variant 3 (mark 2), while among trenchless methods the bigger grade was putted for directional drilling method (mark 5) – because of possibly smaller initial and final excavations. Costs of substitute water delivery was the highest in variant 1 (mark 2), because of necessity of cleaning the existing pipeline with hydrodynamic method. Costs of roadway surface reconstruction and costs of potential investment risk were the highest in trench method, while among trenchless methods bigger mark got the directional drilling method.

The time criterion, very important from the investor point of view, was estimated in accordance to preparation, installation and reconstruction time. Preparation works are the shortest in trenchless methods, and weather conditions do not determinate this methods significantly. That is why variants 1 and 2 were marked with a 4 grade, while variant 3 with a grade 2 (relatively long preparation time). All 3 analysed methods characterize with comparatively small pipe installation time – variants 2 and 3 were marked with a 3 grade, while the method of a static cracking replacement was marked with 4. Road reconstruction time was estimated as the longest in traditional method. In trenchless methods, the road will be relatively reconstructed quicker in variant 2 because of smaller initial and final excavations (mark: 4).

The risk of groundwater contamination was estimated as small in variant 2 (mark: 4) and as moderate in methods 1 and 3 (marks: 3). Due to small excavations in variants 1 and 2, the risk of groundwater table lowering is low (marks: 4), while in traditional method – moderate (mark: 3). However, in traditional excavation method, the risk of fumes and noise level rising is relatively small (mark: 4), while in trenchless methods it was estimated as high (marks: 2). The smallest possibility of damaging the municipal greenery was estimated in horizontal drilling method (mark: 4), while the biggest in traditional method (mark: 2).

Table 2. Marked main and sub- criteria for variants 1, 2, 3

No	Main criterion	Weight	No.	Sub-criterion	Weight	Mark		
		[%]			[%]	v.1	v.2	v.3
1	Technical	10	1.1	realization possibility	50	4	4	2.5
			1.2	material application	35	5	5	5
			1.3	operational conditions	15	3	3	4
						4.2	4.2	3.6
2	Economical	31	2.1	excavation, drainage	25	4	4	1
			2.2	roadway occupation	25	4	5	2
			2.3	substitute water supply	20	2	4	3
			2.4	roadway reconstruction	20	3	4	1
			2.5	investment risk	10	3	4	2
						3.3	4.25	1.75
3	Time	25	3.1	preparation	30	4	4	2
			3.2	installation	40	4	3	3
			3.3	roadway reconstruction	30	3	4	1
						3.7	3.6	2.1
4	Ecological	20	4.1	groundwater contamination	30	3	4	3
			4.2	groundwater lowering	30	4	4	3
			4.3	fumes, noise	20	4	4	2
			4.4	greenery damage	20	3	4	2
						3.5	4	2.6
5	Social	14	5.1	excessive noise	30	4	4	2
			5.2	roadway occupation	40	3	4	2
			5.3	water supply hindrance	30	4	5	3
						3.6	4.3	2.3
FINAL MARK						3.57	4.04	2.27

The first social sub-criterion is highly related to a risk of noise level rising sub-criterion and therefore marks for all 3 variants were the same as in 4.3 sub-criterion. The biggest roadway occupation problems are in traditional method, where the whole roadway is out of order (mark: 2). The substitutional water supply delivery was marked positively in all 3 variants (marks: 4, 5, 3). Detailed main and sub-criteria are presented in table 2.

3.2. Results discussion

The building of new water supply pipeline in a horizontal directional drilling method was evaluated with a final mark 4.04, what in 5-grade scale can respond as a grade: good. The variant 2 was evaluated as the best in almost all categories among the analysed methods. The method of a static cracking replacement of a pipe was finally marked as 3.57. The traditional method (variant 3) was evaluated as the worse among three analysed cases: final mark 2.27.

The final method was calculated as a weighted arithmetic mean of all sub-criteria marks. Taking into account only the technical criterion, variants 1 and 2 were estimated with identical marks 4.2. The method of traditional excavations was evaluated significantly lower because of many contraindications. The economical criterion showed the advantage of a variant 2, which was grade with 4.25. Theoretical costs of realization were the biggest in variant 3 due to the necessity of the whole roadway occupation. The variant of a static cracking method was evaluated as the best in time criterion, while the horizontal directional drilling method was evaluated as the best in ecological method. The smallest social inconveniences were estimated in variant 2.

4 Summary and Conclusions

The multi-criteria decision analysis of 3 rehabilitation methods showed that in the case in question the best possible variant is a horizontal directional drilling method, which was evaluated with the highest final mark and the highest partial marks in 4 out of 5 sub-criteria. The decision evaluation tools can be very helpful during the decision process, due to the fact that the selection of a chosen method can be supported and explained with rational and factual reasons. Is also could help to avoid the situation, in which the financial issue is the only criterion determining the method selection. However, it should be underlined that the most difficult part of multi-criteria decision analysis is criteria identification and weighting.

References

1. Bergel T., Kaczor G., Bugajski P.: Stan techniczny sieci wodociągowych w małych wodociągach województwa małopolskiego i podkarpackiego. *Infrastruktura i ekologia terenów wiejskich*, 3/IV, 291–304, 2013.
2. Chwiałkowska J.: Bezwykopowe metody renowacji sieci wodociągowej na przykładzie miasta Bydgoszczy. *Inżynieria i Ochrona Środowiska*, 15 (4), 373–386, 2012.
3. Dąbrowska W.: Zagrożenia jakości wody pochodzące od materiałów do budowy sieci i instalacji wodociągowych. *Materiały konferencyjne: Nowe technologie w sieciach i instalacjach wodociągowych i kanalizacyjnych*. Ustroń, 181–187, 2004.
4. Dohnalik P., Jędrzejewski A.: Efektywna eksploatacja wodociągów. LEMtech Konsulting Sp. z o.o., Kraków 2004.
5. Figueira J., Greco S., Ehrgott M.: Multicriteria decision analysis: state of the art surveys. *Springer*. New York, 2005.
6. Knapik K., Bajer J.: Wodociągi. Wyd. Politechniki Krakowskiej, Kraków 2011.
7. Książek M.: Analiza porównawcza wybranych metod wielokryterialnych oceny przedsięwzięć inwestycyjnych. *Budownictwo i inżynieria środowiska*, 2/2011, 555–561, 2011.
8. Kuliczkowski A.: Ekspertyzy konstrukcyjne przewodów wodociągowych sposobem na eliminację ich awarii. *Nowoczesne budownictwo inżynieryjne*, 6 (39), 58–61, 2011.
9. Kuliczkowski A., Kuliczkowska E., Zwierzchowska A., Zwierzchowski D., Dańczuk P., Kubicka U., Kuliczkowski P., Lisowska J.: Technologie bezwykopowe w Inżynierii Środowiska. Wyd. Seidel-Przywecki Sp. z o.o., Warszawa, 2010.
10. Kusak M., Kwietniewski M., Udoł M.: Wpływ różnych czynników na uszkadzalność przewodów sieci wodociągowych w świetle eksploatacyjnych badań niezawodności. *Gaz, Woda i Technika Sanitarna*, 10, 366–371, 2002.
11. Kwietniewski M., Leśniewski M.: Materiały przewodów wodociągowych i kanalizacyjnych w aspekcie ich niezawodności. *Gospodarka wodna,* 4/2007, 158–166, 2007.
12. Kwietniewski M.: Awaryjność infrastruktury wodociągowej i kanalizacyjnej w Polsce w świetle badań eksploatacyjnych. XXV Konferencja Naukowo-Techniczna, Międzyzdroje, 127–140, 2011.
13. Lade O., Oloke D., Chinyio E., Fullen M.: Use of multi-criteria decision analysis methods for water supply problems: A framework for improved rainwater harvesting. *Journal of Environmental Science and Engineering*, A1 (2012), 909–917, 2012.
14. Mielcarzewicz E.: Modernizacja sieci wodociągowych i kanalizacyjnych. *Ochrona Środowiska,* 2(65), 3–8, 1997.

15. Mucha Z., Mikosz J., Generowicz A.: Zastosowanie analizy wielokryterialnej do wyboru technologii w małych oczyszczalniach ścieków. Czasopismo Techniczne z. 4 Środowisko z. 1-Ś. Wyd. Politechniki Krakowskiej, 143–155, 2012.

16. Piechurski F. G., Dzikowski T.: Ocena kosztów renowacji i wymiany rozdzielczej sieci wodociągowej. *Nowoczesne Budownictwo Inżynieryjne*, 3 (42), 30–34, 2012.

17. Prusak B.: Metody oceny projektów inwestycyjnych. *Zeszyty Naukowe Politechniki Gdańskiej. Ekonomia*, 39 (586), 121–130, 2001.

18. Scholten L., Scheidegger A., Reichert P., Maurer M., Lienert J.: Strategic rehabilitation planning of piped water networks using multi-criteria decision analysis. *Water Research*, 49, 124–143, 2014.

19. Tchórzewska-Cieślak B., Rak J.: Awaryjność sieci wodociągowych w głównych miastach Doliny Sanu. III Konferencja Naukowo – Techniczna „Błękitny San”, 113–123, Dubiecko 2006.

Analysis of a condition of exploited concrete sewerage manholes

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Abstract

Sewer manholes are essential elements of gravity sewerage systems. The wide range of market offers includes both plastic and concrete sewer manholes. In order to fulfil its function and make its long-standing, proper exploitation available, manholes should be made of high quality materials. The apparent ease of producing sewerage manholes prefabricated elements and low quality materials used by some producers caused that concrete manholes seem to be impermanent. However, the technology of prefabrication and principles of concrete manholes realizations are continuously improved. Nowadays, the building of concrete manholes which enables a long-time proper exploitation is possible and often applied.

This paper presents results of an evaluation and analysis of the condition of 41 concrete exploited sewerage manholes of gravity sanitary systems and gravity storm water drainage systems. Manholes were located in 13 different testing points in 5 voivodeships in Poland. The exploitation time of examined sewer manholes varied from 1 to over 11 years. During the test, the general condition of manholes was valuated as well as the condition of manhole base units. Information about every manhole was supplemented with the manhole's exploitation time, localization, system type and manhole base unit producing technology. As additional, in selected cases also examinations of sewage pH and concrete pH were executed. The sewage and concrete pH was examined by the Rainbow-Test method indicator. Basing on executed analysis, a dependence rule between technical condition of a manholes and their time of exploitation and producing technology were tried to be defined.

Keywords

concrete, sewerage manhole, invert channel, pH Rainbow Test

1 Introduction

Sewer manholes are essential elements of gravity sewerage systems, which enable the inspection, cleaning and ventilation of sewers but also guarantee undisturbed sewage flow in places of change of direction, section and slope or sewer connections (*Heridrich, 1999*). There are plenty of different kinds of sewer manholes depending on their function, size or material (*PN-B 10729-1999*). The wide range of market offers includes both plastic and concrete sewer manholes.

In accordance to European Standard implemented into Polish Law, concrete is defined as a composite material created by mixing fine and coarse aggregate with water and possible additional admixtures, which hardens over time due to the hydration reaction of cement (*PN-EN 206:2014-04*). The kind of a concrete highly influence the exploitation process of a sewerage concrete manholes. Therefore, concrete elements used in sewerage systems should be made of concrete of restrictive parameters. The class of used concrete should be adjusted to predicted working conditions of a concrete element. Sanitary and storm manholes are exposed to many different destructive factors from groundwater, precipitation and sewage but also from biological and mechanic influence (attrition and cavitation) (*Jaśniok and Jaśniok, 2007*). Usually, pH of social sewage varies between 6.5–8.5, while concentrations of aggressive substances (sulfate salts, chlorides and nitrites) are respectively small (*Gruener, 1983; Wysocki, 2009*). The environment of such parameters is qualified as slightly aggressive to a concrete of a XA1 class. The protection against corrosion processes for XA1 class is a concrete itself (*PN-EN 206-1:2003*). However, occasionally sewage can contain significant amounts of organic compounds, which during decomposition produce hydrogen sulfide. The sulfur, created in the oxidation process of hydrogen sulfide, can accumulate on concrete surface above the level of sewage flow. The oxidation of sulfur into the sulphuric acid by *Thiobacillius* bacteria cause that the internal environment of a sewerage manhole is defined as a highly aggressive to a concrete of an exposition class XA3 (*Wysocki, 2009*). The concrete exposed to an environment of these parameters should characterize by: minimal class – C35/45, w/c ratio – 0.45 (amount of water to amount of cement used for concrete), minimal cement amount in 1000 kg of concrete – 360 kg, kind of cement – HSR, water absorption < 6% (recommended: maximum 5%) (*PN-B-01801:1982, PN-EN 1917:2004, PN-EN 197-1:2012*). Following parameters should be especially fulfilled also by a sewerage manhole base – the most important element of a sewerage bottom (*Wysocki, 2009*).

The typical concrete sewerage manhole is built by a concrete base (1), concrete rings (2), chimney (4), reduction slab (3), reducing cone (5), adjustment rings (6) and cover slab (7) (*SPEBK, 2010*). The scheme of exemplary concrete sewerage manhole is presented in figure 1. The base section of a standard manhole is built by bottom connected with vertical walls, bench and invert channel. The base section of a manhole should be equipped with flexible pipe connectors in order to ensure waterproofness of connections (*Florek, 2011*).

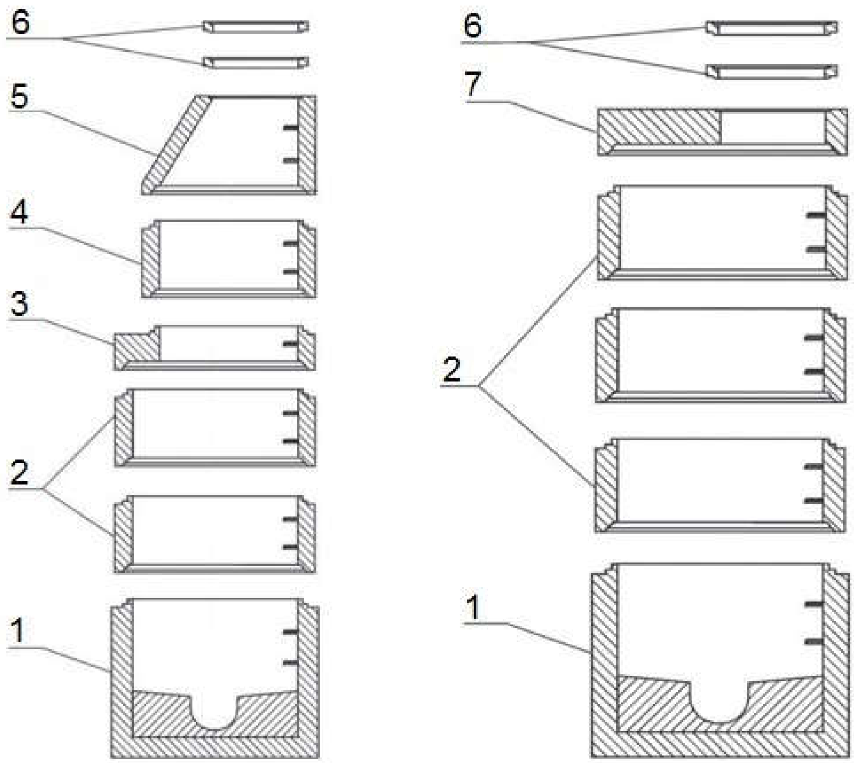

Fig. 1. The exemplary scheme of a concrete sewerage manhole (*SPEBK, 2010*):
1 – manhole base, 2 – concrete rings, 3 – reduction slab, 4 – chimney, 5 – reducing cone, 6 – adjustment rings, 7 – cover slab

The process of a manhole construction is usually realised in two-steps: concrete prefabricated elements are firstly produced at the producing plant, later transported into the building site and there installed and connected into a manhole. Connections of particular concrete elements should strictly fulfil producer's requirements. Usually, elements are connected together with a elastomeric gasket (*SPEBK, 2010*) or a cement mortar. The durability of concrete prefabricates, and therefore their parameter's maintenance during exploitation time, depends on used concrete type (*Suligowski, 2006*), production technology and quality of an element (*Suligowski, 2009*). In accordance to traditional methods of producing invert channels, the process was divided into two steps: mechanical compactness of a concrete, and therefore manual invert formation (*Wysocki, 2009*). The production of a high quality invert channel in the traditional method is theoretically possible, but in practice highly difficult (*Suligowski, 2012*). That is because two constructively different concretes (at different stages of aging) are being combined together. In this technology, the concrete class rarely exceeds C15/20. There is also a necessity of adding special supplements into a manually compacted concrete in order to ensure proper invert channel durability (*Wysocki, 2009*). As an alternative to traditional methods of producing manhole bases are high-tech modern technologies, which enable to produce a monolithic manhole base in once step. In that technology the invert channel, bench, bottom and vertical walls of a manhole base are made of homogenous concrete (*PN-EN 1917:2003*), which guarantees high durability of a whole manhole (*Wysocki, 2009*).

The apparent ease of concrete production and multiplicity of producers cause that quality concrete elements can vary significantly. Generally, bad technical condition of traditional sewerage manholes (*Suligowski, 2009*) and relatively low quality of prefabricated elements determined the opinion about low durability of concrete. However, the prefabrication technology is being continuously improving, and therefore present concrete has completely incomparable quality with a concrete over a dozen years old (*Wysocki, 2009*). It should be strongly emphasised that main factor that influence concrete prefabrications physical damages (scratches, cracks, breaks) are low used concrete quality, improper storage, transport and installation, and overloading from transport (*Czarnecki and Łukowski, 2008*). The long and proper exploitation of a concrete manholes can be guaranteed by the material application of a required parameters and by fulfilling basic rules in transportation and installation processes (*Suligowski, 2009*).

This paper presents the analysis of condition of tens of exploited concrete sewerage manholes in order to define their durability. Moreover, the influence of production date and technology on a general condition of manholes was estimated.

2 Materials and Methods

The condition analysis was performed on 41 concrete sewerage manholes located in 13 various localisations in 5 different voivodeships in Poland (Lublin Voivodeship – 5 manholes, Mazovian Voivodeship – 7, Greater Poland Voivodeship – 22, Lubusz Voivodeship – 3, West Pomeranian Voivodeship – 4). The manholes examinations were pursued in a 3-month period (April-June) in 2011 year. The localisation of examined sewerage manholes is presented in figure 2.

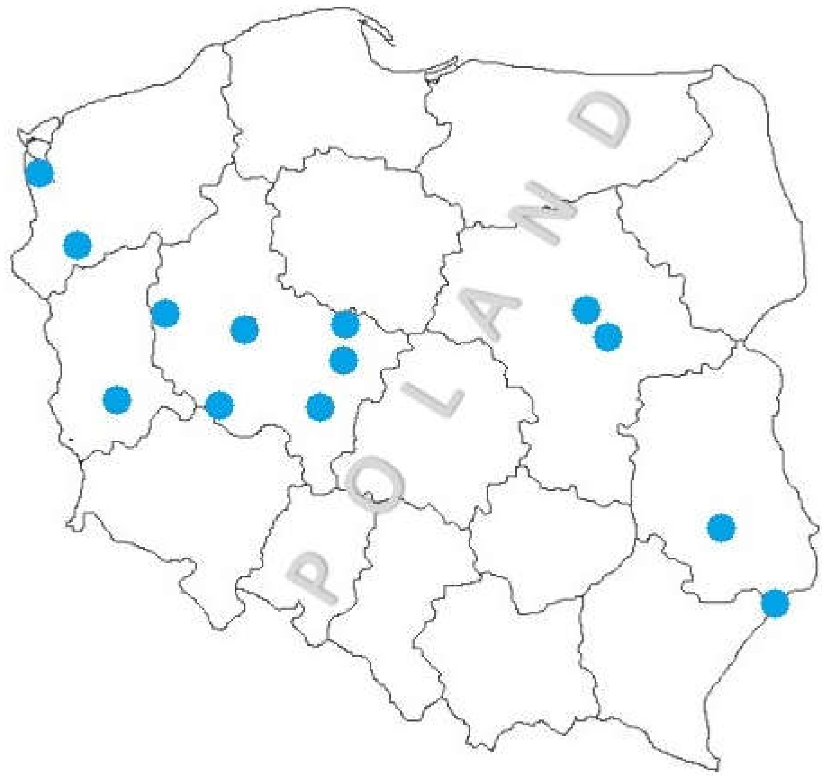

Fig. 2. The localisation of examined sewerage manholes

The methodology of concrete sewerage manholes examination included field inspections, manhole base evaluation, concrete and sewage pH measurement and sewage sample collection for laboratory tests. Additionally, thanks to information from the manholes exploiter, the year and technology of production and exploitation conditions were defined. Basing on local inspection, each manhole and a manhole base were marked separately and then grades were averaged. The grade scale was as following: ideal condition – 6, very good – 5, good – 4, satisfactory – 3, bad – 2. Every time when the grade of a manhole or a manhole base was below 5, it was justified by a significant reason description.

pH measurements of a sewage and concrete were realized in selected manholes – only in manholes where it was possible to collect samples or pursue measurement *in-situ* but in accordance to producers requirements. The pH measurement of sewage samples was realized in CyberScan PCD 6500 tool in Laboratory of Environmental Engineering Faculty in Lublin University of Technology. The pH measurement of concrete manhole base was realized by an *in-situ* Rainbow-Test method developed by Germann Instruments Company.

The pH concrete measurement reveals the pH changes in a section of an examined element on a base of a colour distribution on its surface after the use of an aerosol sprayer. The methodology of measurement included the concrete forging and later spraying the forged place by a Rainbow Indicator liquid, which enable to identify the pH of concrete in the range 5–13. The pH scale – together with respectively marked colours in accordance to a Rainbow Test – is shown in figure 3. The concrete which characterizes with blue or purple colour (pH 11–13) is estimated as a fully protected and free out of carbonation processes. The changing purple colour into a green (pH 9–10) indicates the range of a carbonated zone, while changing green into yellow (pH 7) or orange (pH 5) colour means that a concrete is significantly carbonated.

Fig. 3. pH scale (www.germann.org)

3 *Results and Discussion*

Analysis results of a condition of exploited sewerage manholes are presented in table 1. Each of analysed manholes was described by a number, age, localisation, invert channel technology production (in factory or *in-situ* at the building site), kind of sewerage (sanitary or storm drain), manhole base mark, general manhole mark, averaged manhole grade and eventual description. Additionally, selected manholes were specified also by pH values of a concrete and sewage. The description of manholes includes reasons of grade lowering. The lowest grades were caused mainly by concrete corrosion (CC), steps corrosion (SC) and covering sludge (S). The detailed list of abbreviations used in a table 1 is presented below. Sporadically, significant constructional incorrectness were observed – cracks, breaks or joints leakiness. The majority of examined manholes were located in low occupied roadways, while the rest in sidewalks and greenery.

The average grade of all examined manholes was 4.17 – what means a general averaged condition of manholes was – good. Among examined manholes the most common age was 4 and 6 years old (respectively 20% of all). The rest of manholes was 3 years old (17% of all), 1 (7%), 7 (%), 8 (7%), minimum 11 (7%), 5 (5%), 10 (5%) and 11 (5%). Among 41 manholes there were 33 sanitary sewage manholes and 8 storm drain manholes.

Table 1. The specification of analysed concrete sewerage manholes

No.	Age	Localisation	Invert channel production technology	Type	Sewage pH	Concrete pH	Manhole base mark	Manhole mark	Average manhole grade	Description*
1	5	greenery	in-situ	sanitary	-	-	3	4	**3.5**	CS
2	5	greenery	in-situ	sanitary	-	-	4	4	**4**	S
3	7	roadway	factory	sanitary	-	-	5	5	**5**	-
4	7	roadway	factory	sanitary	-	-	4	5	**4.5**	-
5	7	roadway	factory	sanitary	-	-	5	2	**3.5**	CC
6	4	roadway	factory	sanitary	8.18	12	5	5	**5**	-
7	4	roadway	factory	sanitary	-	13	5	5	**5**	-
8	4	roadway	factory	sanitary	-	13	4	5	**4.5**	SS
9	10	roadway	in-situ	storm	-	10	2	2	**2**	C
10	8	roadway	factory	sanitary	7.08	13	5	4	**4.5**	CC
11	10	roadway	in-situ	storm	-	-	2	2	**2**	SC
12	8	roadway	factory	sanitary	7.21	13	5	4	**4.5**	SC
13	4	roadway	factory	sanitary	-	-	6	5	**5.5**	-
14	4	roadway	factory	sanitary	7.11	13	5	5	**5**	-
15	4	roadway	factory	sanitary	-	-	5	5	**5**	-
16	4	roadway	factory	sanitary	6.78	13	4	5	**4.5**	SS
17	4	roadway	factory	sanitary	-	-	6	5	**5.5**	-
18	6	roadway	factory	sanitary	-	-	5	4	**4.5**	CR
19	6	roadway	factory	sanitary	-	-	5	5	**5**	-
20	6	roadway	factory	sanitary	-	-	3	5	**4**	CS
21	6	roadway	factory	sanitary	7.08	13	3	5	**4**	CS
22	6	roadway	factory	sanitary	7.27	-	5	4	**4.5**	SC
23	6	roadway	factory	sanitary	-	-	5	3	**4**	LC
24	6	roadway	factory	sanitary	6.27	-	4	4	**4**	CS
25	6	roadway	factory	sanitary	6.82	13	4	4	**4**	SC
26	3	greenery	factory	storm	-	-	4	4	**4**	CS
27	3	greenery	-	storm	6.95	-	-	4	**4**	CS

Table 1. The specification of analysed concrete sewerage manholes (cont.)

No.	Age	Localisation	Invert channel production technology	Type	Sewage pH	Concrete pH	Manhole base mark	Manhole mark	Average manhole grade	Description*
28	3	greenery	-	storm	-	-	-	4	**4**	CS
29	1	roadway	factory	sanitary	6.88	13	4	4	**4**	CS
30	1	roadway	factory	sanitary	-	-	4	5	**4.5**	S
31	11	roadway	factory	sanitary	7.24	13	3	4	**3.5**	SC
32	1	roadway	factory	sanitary	-	-	5	5	**5**	-
33	11	roadway	factory	sanitary	7.68	12	4	4	**4**	SC
34	3	roadway	factory	storm	-	13	5	5	**5**	SC
35	> 11	sidewalk	-	storm	7.82	-	4	3	**3**	SC
36	3	roadway	factory	sanitary	7.9	13	5	4	**4.5**	SC
37	3	roadway	factory	sanitary	-	13	5	4	**4.5**	SC
38	3	greenery	factory	sanitary	-	13	5	4	**4.5**	SC
39	> 11	roadway	in-situ	sanitary	7.64	13	2	2	**2**	L, C
40	8	roadway	factory	storm	-	13	5	5	**5**	-
41	> 11	roadway	in-situ	sanitary	-	8	2	2	**2**	L, C

*CS – corrosion signs, S – sludge, CC – cracked cone, SS – small sludge, C – concrete corrosion, SC – steps corrosion, CR – chipped ring, LC – leaking connection, L – leaks

The age structure of analysed manholes is presented in figure 4. Additionally, in figure 4 there is presented an average mark among the same age manholes (values above columns). On each column there is also a percentage share of types of manholes of the same age – sanitary (S) or storm drain (D) and a percentage share of prefabricated invert channels (F) or built in situ (B). 57% of 3 years old manholes were storm drain manholes (43% sanitary), while 71% invert channels of these manholes were prefabricated (no data available for 29% of invert channels). There were a similar structure of 8 years old manholes (67% – sanitary manholes, 33% – storm drain manholes) and minimum 11 years old manholes (67% – sanitary, 33% – storm drain; 67% – prefabricated invert channels, 33% – no data technology available). In other cases, the percentage share of particular groups was 100%.

The averaged general mark higher than 4.17 was observed among six groups of manholes with prefabricated invert channels share equal 100%. These manholes were respectively 1, 4, 6, 7 and 8 years old. Only 11 years old manholes, despite the fact of prefabricated invert channels, were evaluated below the average value (4.17). Also, 3 years old manholes, with majority of prefabricated invert channels (71%) were marked with a grade higher than the average value. On the other hand, manholes (5, 10 and minimum 11 years old manholes) which all or most of invert channels were built *in-situ* were evaluated below 4.17 grade (respectively 3.75, 2.0, 2.33). Despite the general observed trend – the lowering averaged marks together with manhole aging, there are also groups of manholes that were exploited for several years (e.g. 4 and 8 years old manholes) that were evaluated with a general *very good* grade. That can indicate the inference, that more important influence on technical condition of sewerage manholes has the production technology that the manhole age.

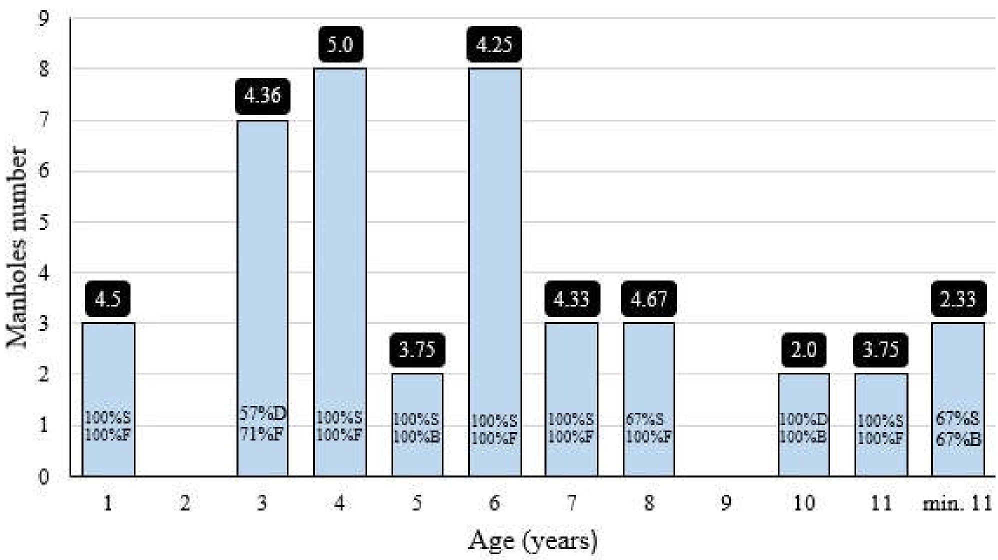

Fig. 4. The age structure of analysed concrete sewerage manholes

Among 16 examined sewage samples from different manholes, the pH range varied between 6.27–8.18. That pH range perfectly correspond with a theoretical values (*Gruener, 1983; Wysocki, 2009*), with a slight exception of a low limit exceeding (pH 6.5). The technical local conditions and manhole condition caused that it was possible to perused 20 pH concrete tests by a Rainbow Test method. In a majority of cases, the concrete pH value was between 12–13. Once, the pH value was 8 and 10. In accordance to an applied methodology, pH values equal to 12 (2 cases) and 13 (16 cases) were estimated as s fully protected and free out of carbonation processes. The pH value equal to 10 was measured in a storm drain manhole, with a invert channel made *in-situ* at the building site. The general condition of that manhole was evaluated as *bad*, which was mainly caused by a concrete corrosion. The Rainbow pH Test confirmed that evaluation mark – the pH 10 indicates the range of a carbonated zone. Similar situation was observed in one of sanitary manholes, which invert channel was also made *in-situ* at the building site. Both the manhole base mark, as well as a general manhole mark was 2, what was caused by plural leaks and corrosion. The pH test resulted in value 8 – which confirmed advanced concrete corrosion processes.

Among 41 examined concrete manholes, 32 invert channels were prefabricated, 6 was made *in-situ* at the building site and about 3 there were no production data available. The analysis of manhole's marks confirms the influence between the invert channel production technology and the general manhole condition. On charts in figure 5, there are shown percentage shares of manhole's marks in dependence on invert channel production technology. Among 32 manholes with prefabricated invert channels, only 6% was evaluated below *good*, while among manholes with invert channels built *in-situ* only 2 manholes (16.5%) was in a *good* general condition. Despite the fact, that there were only few manholes with invert channels made *in-situ* at the building site taken into consideration, it can be said that the opinion that building a high quality invert channel in traditional technology is very problematic.

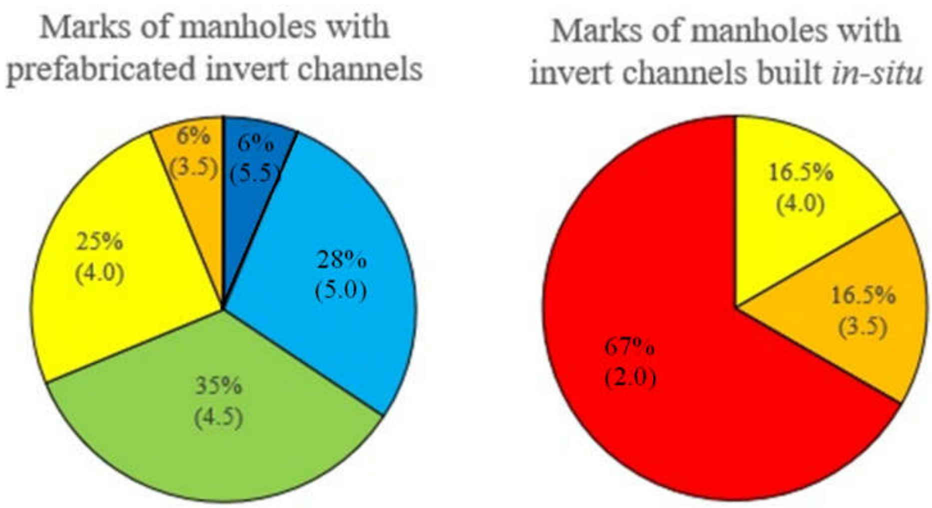

Fig. 5. The percentage share of manhole's marks in dependence on invert channel production technology (colour blue – mark 5.5, azure – 5.0, green – 4.5, yellow – 4.0, orange – 3.5, red – 2.0)

In order to fully present results of pursued analysis, in figure 6 there are shown exemplary photographs of examined concrete sewerage manholes and invert channels, evaluated with different marks (from 6 – *ideal* to 2 – *bad*). Figure 6a presents a manhole number 13, which was evaluated with a grade 5.5. The prefabricated invert channel of that manhole is in a perfect condition, despite the 4 years of exploitation. In figure 6b is shown a manhole 22. The condition of a prefabricated invert channel after 6 years of exploitation was *very good*, and the general mark (4.5) was caused mainly by corrosion of manhole steps. The exemplary manhole base in *good* condition is presented in figure 6c (manhole number 30). Despite short exploitation (1 year), the manhole base was evaluated only by 4 grade due to the fact of sludge covering the manhole base. However, it should be noticed that in manhole number 30 there were no visible signs of concrete corrosion or mechanical damages of prefabricated concrete elements. The general condition of that manhole was 4.5. Figure 6d presents the manhole number 1, exploited for 5 years. The invert channel of that manhole, that was built *in-situ* at the building site, was clearly corroded, the bench was in poor condition and was covered with sludge. That is why the manhole base was evaluated only as *satisfactory*. The general manhole grade was 3.5. The exemplary manhole (number 9) in *bad* condition is shown in figure 6e – that storm drain manhole was exploited for 10 years. The evaluation of a manhole base and the general mark was caused by invert channel (made *in-situ*) corrosion, poor bench condition and covering sludge. As an addition, in figure 6f is presented an example of a Rainbow Test.

Fig. 6a. Condition: *ideal* Fig. 6b. Condition: *very good* Fig. 6c. Condition: *good*

Fig. 6d. Condition: *satisfactory* Fig. 6e. Condition: bad Fig. 6f. Rainbow-Test

Fig. 6. Examples of examined manholes and pH Rainbow-Test

4 Summary and Conclusions

The executed analysis shows that examined exploited concrete sewerage manholes were in general *very good* or *good* technical conditions, which confirms the fact that modern concrete can be successfully applied for sewerage manholes. Manholes that were evaluated with the lowest grades were in exploitation for at least 10 years or had invert channels made *in-situ* at the building sites. The *in-situ* high quality invert channel production is possible but very problematic – and therefore it can strongly influence the manhole general condition and implicate manhole durability shortening. Similarly to other materials, the proper transportation and storage of concrete elements, and further the fulfilling of installation and maintenance requirements, make the long-term concrete manhole exploitation possible.

References

1. Czarnecki L., Łukowski P.: Naprawy i ochrona konstrukcji betonowych w świetle norm europejskich. *Budownictwo, Technologie, Architektura*, 4 (44), 52–55, 2008.
2. Florek M.: Ekonomika stosowania betonu w systemach kanalizacyjnych. *Polski Instalator*, 2, 68–71, 2011.
3. Gruener M.: Korozja i ochrona betonu. Arkady, Warszawa 1983.
4. Heidrich Z.: Kanalizacja. WSiP, Warszawa 1999.
5. Jaśniok M., Jaśniok T.: Charakterystyka procesu korozji zbrojenia w betonie. Metody diagnostyki zagrożenia korozyjnego zbrojenia w konstrukcjach żelbetowych (cz.1). *Przegląd Budowlany*, 2 (78), 20–25, 2007.
6. PN-B-01801:1982. Antykorozyjne zabezpieczenia w budownictwie – Konstrukcje betonowe i żelbetowe – Podstawowe zasady projektowania.
7. PN-B-10729:1999. Kanalizacja – Studzienki kanalizacyjne.
8. PN-EN 1917:2004. Studzienki włazowe i niewłazowe z betonu niezbrojonego, z betonu zbrojonego włóknem stalowym i żelbetowe.
9. PN-EN 197-1:2012. Cement – Cz. 1: Skład, wymagania i kryteria zgodności dotyczące cementów powszechnego użytku.
10. PN-EN 206:2014-04. Beton – Wymagania, właściwości, produkcja i zgodność.
11. PN-EN 206-1:2003. Beton – Cz.1. Wymagania, właściwości, produkcja i zgodność.
12. SPEBK – Materiały edukacyjne – Praca Zbiorowa, Stowarzyszenie Producentów Elementów Betonowych dla Kanalizacji, 2010.
13. Suligowski Z.: Betonowe elementy kanalizacji – czy dodatkowo izolować od zewnątrz? Malowana studzienka. *Magazyn Instalatora*, 1 (125), 48–49, 2009.
14. Suligowski Z., Bolt A.: Aktualne zagadnienia stosowania kanalizacyjnej studzienki rewizyjnej. Cz. 1. *Forum Eksploatatora*, 5 (26), 36–39, 2006.
15. Suligowski Z.: O kanalizacyjnej studzience rewizyjnej. *Ochrona Środowiska. Gospodarka Komunalna*, 3–4 (603), 16–23, 2012.
16. www.germann.org
17. Wysocki L.: Zagrożenia korozyjne w studzienkach kanalizacyjnych. *Nowoczesne Budownictwo Inżynieryjne*, 2 (23), 58, 2009.

Reconstruction and modernization of urban water networks

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Abstract

The basic features and problems of operating water networks of settlements in Ukraine are described. The most rational ways of urban water networks' improvement are determined on the basis of the results of their research to improve water supply city and to provide resource-saving. The mathematical model of technical and economic calculations is developed taking into account the changes of the basic influential parameters during the whole term of project realization to ground the feasibility of structural changes of urban water networks during its reconstruction and modernization. The mathematical models and calculation methods of water networks are defined and described: the determination of the economical pipelines' diameters; hydraulic resistances' increase of pipelines; the analytical function of integral distribution of water flow rates for water consumption modelling; the maximum coefficients of water consumption variation; relationship of water flow rates increase on free pressure values and etc. Application of this models allows taking into account changes of water networks' parameters during operation and defining the optimal ways of its reconstruction and modernization according to normative indexes of reliable operation and providing users by water. The modelling of separate elements of water networks and modes of their combined operation with confunction buildings is provided for more than 30 towns. On the basis of the conducted researches and application of the offered methods during modernization of water networks allowed to stabilize water-supply, reduce the electric power consumption and water losses, that is confirmed by calculations and actual results on operating water networks.

Keywords

water networks, pumping stations, water consumption, water losses, water leakages, excess pressures

1 Introduction

Tekst The operation of the water supply system must be reliable, economical, energy-conserving and efficient to achieve the rational water use, environmental protection and other requirements (*Building norms and regulations, 2013; Recommendations*). These requirements belong to the most valuable, sizeable and technologically difficult part of the water supply system of settlements in Ukraine – water network which is in hydraulic confunction with pumping stations and pressure-regulative buildings (*Tkachuk et.al., 2011; Tkachuk, 2008*).

The urban water network is characterized by structural complication, dynamics of state and imperfection of operation (even for small objects the water network is hundreds of kilometres of water mains and water distribution networks from pipes of different materials and diameters, constructed in different years, few powerful base and booster pumping stations, pressure-regulative buildings by capacity of ten thousands m^3).

The present imperfections in water networks' operation are caused not only by unsatisfactory state of the buildings (wear-out and accidence of water networks, water losses and other) but also by their parameters mismatch and structural layouts with new operating conditions. It results the unsatisfactory providing users by water, the increase of construction cost of water networks and operating costs on its maintenance, excessive consumption of electric power on water supply.

The conducted researches show that operation of urban water networks nowadays has the characteristic features connected with permanent changes of its parameters. That is why it requires the detailed analysis of these tendencies and its improvement to stabilize water-supply and to save resources use.

There are such basic features of operating water networks of settlements in Ukraine:

- *reduction of supplied water volumes* (conditioned by reduction of industry water consumption, installation of water account, increase of electricity prices and water rates);
- *increase of unaccounted water losses* (leakages, irrational water consumption, unauthorized water flow rates);
- *increase of accidence* of pipelines and equipment connected with its ageing, low level of planned and preventive maintenance service, late repairs and replacement (sometimes with its absence at all);
- *degradation of hydraulic characteristics* of water mains and networks (hydraulic resistance increase of pipes, non-constructive changes in the networks layouts and etc.);

– *reduction of total, but increase of specific electric power consumption* connected with ageing and wear out of pumping units;
– *reduction of reliability indexes* connected with ageing and wear out of buildings, pipelines and equipment, low level of its replacement or renewal.

70% of electric power is consumed by water and sewage utilities of settlements in Ukraine to supply drinking water in water networks. Thus the average specific electric power consumption on water supply is about 1 kW-h/m^3, and the irrational electric power consumption makes 30% and more.

Most water pipelines are under operation more than 30 years that negatively affects not only on their hydraulic characteristics but also on reliability indexes. The third part of municipal water networks (more than 37 thousands km) requires replacement because of intensive ageing and wearing out of pipelines. The accidence of pipelines increases during operation because of the corrosion (especially steel pipes). This results the increase of hydraulic resistances of pipes in 1.5...5.0 times and more.

One of the most influential factors on the accidence of networks and water losses values is water pressure (*Thorton and Lambert, 2005; Veljanoski and, Pelivanoski, 2001; Tkachuk and Khomko, 2008; Tkachuk and Novytska, 2009; Tkachuk, 2008; Novytska, 2013*). That is why many countries regulate the values of maximally permissible pressures in water networks. The value of water pressure was 60 m according to old standards in Ukraine and from January 2014 is 45 m (*Building norms and regulations, 2013*). The observance of these normative pressure values considerably reduces the accidence of pipelines, water leakages and irrational water use.

The secondary water pollution takes place during its transmission and distribution by water networks. In the result, the high-quality treated water at water treatment plants does not meet the modern normative requirements in the points of its distribution.

Such state of water networks requires the necessity of its improvement and complete renovation of pipelines and equipment. The very important issue is a change of design conditions, its reconstruction and modernization taking into account the present problems and progress trends, change of basic parameters during operation, and also resource-saving.

Water networks' optimization works provide the definition of the most rational variant of improvement of their layout, parameters and operation modes taking into account normative engineering constraints, providing all users by water at pressures not exceeding sufficient, efficiency and reliability conditions. There are many algorithms and methods of water distribution networks' optimization (e.g.

Bolognesi et.al., 2014; Geem, 2015; Klernpous et.al., 1997; Mansouri et.al., 2015; Sârb., 2010; Marques et.al., 2012).

The diagnostics, adjusting and optimization works are conducted on operating water networks (*Tkachuk, 2007; Tkachuk, 2008*). The modelling of separate elements of water networks and modes of their combined operation with confunction buildings is provided for this. All calculations are made on this basis at designing of new and reconstruction of operated water networks and at efficiency estimation during operation.

2 *Aim of researches*

Optimization of water supply networks of the city requires taking into account many factors, determining their state, interaction with other confunction buildings and must be based on the modern mathematical tool allowing modelling many elements and operation modes. Many present methods of water networks calculations do not take into account changes of influential parameters during operation, relationships of water flow rates on pressure values. In addition, there are no determination methods of design water flow rates depending on the set supply levels and water networks categories. The calculations of economical pipelines' diameters and determination of structural layouts of water networks do not take into account their indexes of reliability and stochastic changes in operation modes.

The researches provide the definition of the most effective ways of the indicated issues' decision and ground the possibility of the received results' application during optimization of water networks.

3 *Methodology*

The optimization criterion of urban water network can be taken as discounted value of total finance expenses on construction, maintenance of the networks and confunctioned buildings (*Tkachuk, 2008*). This criterion defines the most rational variant of water networks' improvement if networks' parameters meet normative engineering constraints and reliability conditions

$$B_d = \sum_{t=0}^{T} \frac{K_t + B_{op\,t}}{(1+e)^t} \rightarrow \min \quad , \tag{1}$$

where: K_t – the cost of construction works of *t* year; Bop_t – operation costs in *t* year; *T* – a term of project realization [year]; *e* – a discount coefficient [-].

The search of optimal parameters of the network or its layout comes to finding of minimum values B_d discounted to the beginning of project realization. That is why all values in equation (1) are considered as mathematical dependences and studying of their general expression (goal functions) on extremum is conducted. On the basis of this method the analytical expressions are determined for defining the economical pipelines' diameters of the network, pumping stations parameters feeding the water network, booster pump stations etc.

The determination of the economical pipelines' diameters of the water network and water mains can be expressed by the formula (*Tkachuk, 2008; Tkachuk, 2009*).

$$d_{ec} = E \cdot k_{qt} \cdot Q_{av.PS.o}^{\frac{\beta+1}{\alpha+m}} , \tag{2}$$

where: E – a parameter which takes into account the indexes of construction and operation costs of the pipeline (economic factor) [-]; E can be accepted from 0.8 to 1.1 for conditions in Ukraine; k_{qt} – the generalized coefficient of the relative load of the pipeline branch [-], $Q_{av.PS.o}$ – annual average water discharge into water network at the initial period [m^3/s], α, β, m – exponents depending on pipe material, given in Table 1(*Tkachuk, 2008*).

Table 1. Values of the coefficients and exponents for pipes of different materials

Pipes material	k	B	m	α
Steel	0.00148	1.93	5.08	1.1/1.15
Cast-iron	0.00163	1.81	4.90	1.6/1.5
Reinforced-concrete	0.00169	1.85	4.89	2.05/2.4
Plastic	0.00105	1.774	4.774	1.8/1.5

Notes: 1. Coefficients k are accepted for q in m^3/s and d in m.

2. The values of parameter α are accepted: above the line – for arterial mains and under the line – for water networks.

The generalized coefficient of the relative load of network's section k_{qt} is expressed by formula (*Tkachuk, 2008*):

$$k_{qt} = \left(\frac{k_L{}^{\beta}}{n}\right)^{\frac{1}{\alpha+m}} \; k'_{qt}, \tag{3}$$

where: k_L – a coefficient of branch load [-], determined as relation of total water flow rates on the branch to water discharge of the pumping station for design mode on average water consumption at the initial period, n – the amount of pipeline lines in the networks' section on the given branch [-], k'_{qt} – is a multiplier [-] which takes into account the change of influential parameters and is expressed by the formula:

$$k'_{qt} = k_{q\sigma} \;\; k_{q\eta} \;\; k_{qt} \;\; k_{qK}{}^{2} \;\; k_{qe} \;\; k_{qT} \, , \tag{4}$$

where: $k_{q\sigma}$, $k_{q\eta}$, k_{qt}, k_{qK}, k_{qe}, k_{qT} – coefficients [-] which take into account the change of electricity prices, efficiency factor of pumping units, water consumption values, variation of water supply, discount coefficient and terms of projects' realization, respectively, determined by empirical formulas and by nomograms (*Tkachuk, 2008*).

These coefficients are determined as relation of design parameters to present values (k_{qK}, k_{qe} and k_{qT}) or by the formulas ($k_{q\sigma}$, $k_{q\eta}$ and k_{qt})

$$k_q = 1 + a \quad t\,, \tag{5}$$

where: a – a coefficient of change during the year of electricity price, pumps efficiency factor or water consumption values [1/h]; t – an operation term [year].

The next equation is received for calculation of coefficients of hydraulic resistances' increase of pipes (*Tkachuk, 2007; Tkachuk, 2008; Tkachuk et.al., 2011*)

$$K_s = 1 + a_2 \left(1 + \frac{0.02554}{d_p}\right) \; lg(1 + a_1 \quad t), \tag{6}$$

where: a_1 – parameter which takes into account continuity of pipeline's operation in the «main mode» [1/h], a_2 – a coefficient which takes into account the influence of the basic factors on hydraulic resistances' increase, d_p – a design value of pipe internal diameter (equal to the diameter of new pipes $d_p = d$) [m].

The computer programs (*UWM, GRS, PWS* etc.) and program modules in the Microsoft Excel (*TEP_дек.xls, kfQ.xls, Пог_вuтр.xls* etc.) were created for usability (*Tkachuk, 2008; Tkachuk et.al., 2011*) which allow automating the indicated calculations.

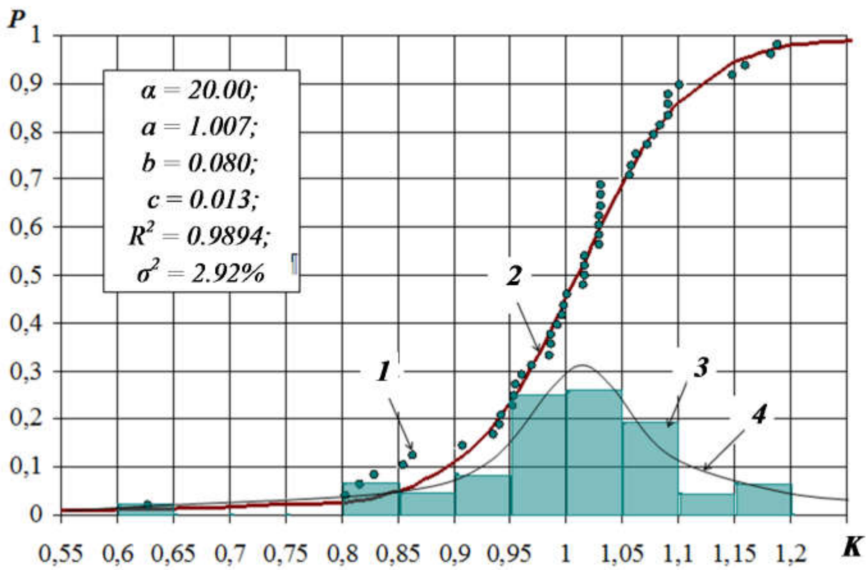

Fig. 1. Characteristic diagram of the integral distribution of daily variation coefficients of water consumption: 1 – experimental data, 2 – analytical function of distribution (Eq. 7), 3, 4 – respectively experimental and theoretical relationships of density distribution function

The analytical function of integral distribution of water flow rates was received for water consumption modelling on operating water networks (*Tkachuk, 2008*). This function which sets adequate relationship of water distribution probability P on variation coefficients K taking into account the dominant local factors in water supply and distribution modes

$$P = \frac{e^{\alpha(K-a)} + c}{e^{\alpha(K-a)} + e^{b/K}}, \quad (7)$$

where: α, a, b and c – parameters which depend on variance function σ^2 of water flow rates distribution density, type of its integral curve, its dislocation (asymmetry) and are determined by approximation of statistical information (Fig. 1).

The method of statistical analysis of water distribution is offered for practical application in the range of design demand rates P_o = 0.95...0.999 (*Tkachuk, 2008*) defining the maximum coefficients of water consumption variation by the formula:

$$K_{max} = 1 + \frac{1}{\alpha} \ ln\left(\frac{1-P_o}{P_o}\right), \quad (8)$$

where: α – an index in Eq. 7 determined by statistical data of water consumption.

The numerical values of readiness factors and demand levels were determined (Table 2) on the basis of estimation of accidence flow influence, technical state of water networks on reliability of water transmission and distribution systems and compability of their structural layouts with the set supply levels of users by water.

Table 1. Proposed to standard the values of time of water supply reduction T_r, readiness factors K_r and water supply levels P_o

Category	Time of water supply reduction				Supply levels P_o of water flow rates	
	up to 30 %		on 30..100%			
	$T_{r(30)}$ [days]	K_r	$T_{r(>30)}$ [hour]	K_r	daily	hourly
1	3	0.90	6	0.99	0.01	0.005
2	10	0.75	12	0.98	0.03	0.01
3	15	0.60	24	0.97	0.04	0.015

The following theoretical analytical relationship of water flow rates increase on free pressure values caused by water leakages and non-productive water flow rates are expressed as (*Novytska, 2013; Novytska and Tkachuk, 2014*):

$$q_{tot} = q_s \ \ k = q_s \ \left(\frac{P}{P_s}\right)^{\chi}, \quad (9)$$

where: q_s – the total water flow rate at sufficient pressure P_s, P – a free pressure in the network [m], χ – an exponent which depends on technical state of the pipelines, local conditions of water distribution etc.

The exponent χ is essentially a numerical characteristic of how water flow rates change depending on the pressure. Its theoretical values are in the range 0.5...2.5, and its actual values can be determined on the basis of field observations or it can be determined at pressures more than sufficient $P > P_s$ by the equation (*Novytska, 2013; Novytska and Tkachuk, 2014*):

$$\chi = 0.95 \quad K_m^{0.6\ 5}; \tag{10}$$

where: K_m – a regression coefficient which depends on water distribution conditions, total water leakages and water losses and can be expressed by the formula:

$$K_m = 6.36 \quad \alpha \quad \gamma + 0.26, \tag{11}$$

where: α – the coefficient of water losses from the total water consumption [-], γ – the coefficient of water losses in dwelling houses from the total water losses [-].

Coefficients α and γ theoretically take values in the range from 0 to 1. The extreme values for γ are $\gamma = 1$ for the case when water losses are caused by excess pressure only in the residential area, and $\gamma = 0$ for the case for leakages presence in the external water-supply network. In real cases of water distribution for Ukraine, we have $\alpha = 0.1...0.9$ and γ=0.4...0.8.

When considering relationships which do not entail the increase of water flow rates with growth of water pressures, coefficient K_m should be taken to be equal to zero. The theoretical computations show that the values of K_m are in the limits from 0.26 to 6.62.

4 Results and Discussion

It is important to take into account standard requirements and engineering constraints defining the layouts of water networks. The optimization calculations are conducted if technical equivalence of possible variants of water supply takes place taking into account the influential factors and local conditions (networks' layout, users' arrangement, relief and etc.). Such approaches of optimization of operating water networks allow supporting of free pressures maximally close to sufficient in every district of the network. It results the minimization of excess pressures and, as a result, reduction of water losses caused by leakages, reduction of network's accidence and electric power consumption on water supply.

The conducted analysis on the basis of the received results of researches allowed determining the feasibility study of water network arrangement using their most widespread layouts. It is determined that while grounding the water mains and water networks layouts it is always reasonable to arrange basic part of water pipelines with minimum possible diameters, and the most important water mains – with increased economical diameters of minimum length. The most economical variant is that in which diameters values of water pipelines piped in one-way considerably differ from each other. It results the underlying reason for arrangement of new water supply system with zoning of water networks (*Tkachuk et.al., 2011; Tkachuk, 2008*).

On the basis of the conducted research and application of the offered methods during optimization of water networks (for more than 30 towns) allowed to stabilize water-supply, reduce the electric power consumption and water losses, that is confirmed by calculations and actual results on operating water networks.

It is offered to divide water supply system of Rivne town into zones and districts on the basis of long-term researches of its operation. The four basic zones (Fig. 2) are proposed by this layout. The zones are feeded by separate pumping stations and three districts are connected to water networks by pressure regulating devices.

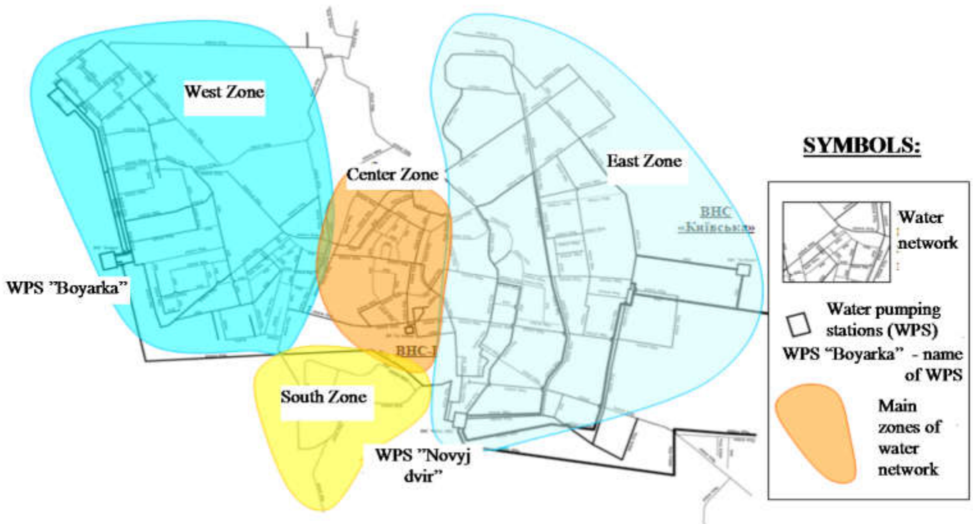

Fig. 2. Layout of zones of Rivne water supply system

The pressures in the water networks of each zone and district must be maximally close to the sufficient ones at the different modes of water consumption. Therefore, it is suggested to conduct pressure regulating at the pumping stations outputs depending on pressures at the control points of water networks of every zone. The districts are defined for water networks for the groups of multi-storeyed buildings of every zone to be maximally close to the sufficient pressures. The water is supplied by booster pumping stations to these buildings.

The changes in water supply technology to town users provided renewal of continuous water supply, pressure regulation in the network, renovation of wear out pumping equipment. The sanation (cementation of internal pipe surface, piping of polyethylene pipes inside of wear out metallic) and replacement, in particular, by plastic pipes, is conducted to reduce water losses caused by leakages from wear out pipelines. In addition, the considerable work is conducted to rationalize water consumption in a dwelling sector (installation of building and residential water-meters with free tests, replacement of buildings' networks and water taps, culture popularization of water consumption in mass-media and etc.).

The implementation of these measures in Ivano-Frankivsk water network (Fig. 3) allowed stabilizing water-supply of the city considerably extending the variation of water demand patterns, and for separate districts – continuously. The volumes of water realization are stabilized, the water losses, total and specific electric power consumption are reduced on 24% comparatively with a period before the introduction of optimization measures.

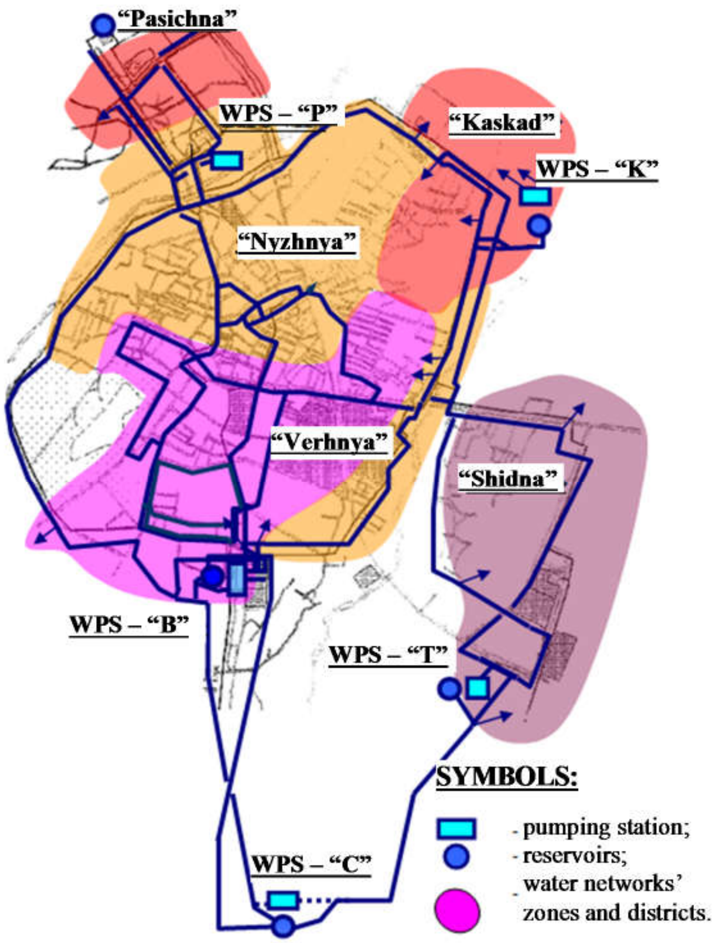

Fig. 3. Layout of zones and districts of Ivano-Frankivsk water network

The hydraulic calculations of the combined operation of water network with confunction buildings are conducted to ground the new layout of Ivano-Frankivsk water network and to verify the compliance of some parameters with local technical requirements. The mathematical model is created for this which includes the design layout, relationships describing the dependences between operating parameters and design characteristics of separate elements of water network.

The conducted works on optimization allowed not only improving the water supply of the city but also reducing the specific electric power consumptions on water supply (below 0.3 kWh/m^3), reducing the accidence of water pipelines up to 0.97 accidents/km/h and water prime price (on 22%).

5 Conclusions

The mathematical model of technical and economic calculations is developed taking into account the changes of the basic influential parameters during the whole term of project realization to ground the feasibility of structural changes of urban water networks during its reconstruction and modernization. The offered approaches of water networks are provided on water networks of more than 30 towns and settlements. Its application allowed stabilizing water supply, reducing the electric power consumption and water losses that is confirmed by calculations and real results on operating water networks.

References

1. Bolognesi A., Bragalli C, Lenzi C., Artina S.: Energy efficiency optimization in water distribution systems. *Procedia Engineering,* 70, 181–190, 2014.
2. Building norms and regulations B.2.5–74:2013. Water supply. External networks and buildings. Design basic. K.: Minregionbud, 2013 (in Ukrainian).
3. Dohnalik P., Jedrzejewski Z.: Efektywna eksploatacja wodociagow. Ograniczanie strat wody. LEMTECH, Krakow 2004 (in Polish)
4. Geem Z. W.: Multiobjective optimization of water distribution networks using fuzzy theory and harmony search. *Water,* 7, 3613–3625, 2015.
5. Klernpous R., Kotowski J., Nikodem J., Ultasiewicz J.: Optimization algorithms of operative control in water distribution systems. *Journal of Computational and Applied Mathematics*, 84, 81–99, 1997.
6. Mansouri R., Torabi H., Hoseini M., Morshedzadeh H.: Optimization of the water distribution networks with differential evolution (DE) and mixed integer linear programming (MILP). *Journal of Water Resource and Protection*, 7, 715–729, 2015.
7. Marques J., Cunha M. C., Sousa J., and Savić D. Robust optimization methodologies for water supply systems design. *Drinking Water Engineering and Science*, 5, 31–37, 2012.

8. Methods recommendations of layout development of central water supply and sewage system optimization. Kyiv (In Ukrainian).
9. Motiee H., McBean E., A. Motiei: Estimating physical unaccounted for water (UFW) in distribution networks using simulation models and GIS. *Urban Water Journal*, 4 (1), 43–52, 2007.
10. Novytska O.: Taking into account actual conditions during hydraulic computations of water networks. *Water Supply and Sanitary Engineering*, 10, 30–35, 2013.
11. Novytska O., Tkachuk O.: Excess water pressure influence on total water consumption by population. *Water Supply and Sanitary Engineering*, 12, 22–27, 2014 (In Russian).
12. Puust R., Kapelan Z., Savic D. A., Koppel T.: A review of methods for leakage management in pipe networks.*Urban Water Journal*, 7 (1), 25–45, 2010.
13. Thorton J., Lambert A.: Progress in practical prediction of pressure/leakage, pressure/burst frequency and pressure/consumption relationships. *Proceedings of IWA Special Conference «Leakage 2005»*, 1–11, Halifax 2005.
14. Tkachuk O., Kosinov V., Novytska O.: Water transmission and distribution systems of settlements. Monograph, NUWM, Rivne 2011 (In Ukrainian).
15. Tkachuk O., Novytska O.: Hydraulic calculations of water supply and distribution networks. *Voda-Magazine*, 10 (26), 50–53, 2009 (In Russian).
16. Tkachuk. O. Hydraulic calculations of operated water pipelines. *Vodopostachanniya ta vodovidvedenniya*. *Vyrobnycho-praktychnyi zhurnal*, 2, 2–6, 2008 (In Ukrainian).
17. Tkachuk O.: Improvement of water transmission and distribution systems of the settlements. Monograph, NUWM, Rivne 2008 (In Ukrainian).
18. Tkachuk O.: Recommendations of economical diameters determination of water networks. *Vodopostachanniya ta vodovidvedenniya*. *Vyrobnycho-praktychnyi zhurnal*, 1, 2–6, 2009 (In Ukrainian).
19. Tkachuk O.: Structural and functional improvement of water transmission and distribution systems. Abstract of Ph.D. thesis (Doctor of Engineering): NUWM, Rivne 2007 (In Ukrainian).
20. Tkachuk O., Khomko V.: Assessment of pressure regulation efficiency in water network of Rivne city. *Bulletin of NUWM*, 2 (42), 346–353, 2008 (In Ukrainian).
21. Tkachuk O.: Ways of function providing of water transmission and distribution systems in terms of ageing and wear out. *Scientific bulletin*, 26, 69–74, 2004 (In Ukrainian).
22. Sârbu I.: Optimization of water distribution networks. *Proceedings of the Romanian academy*, *Series A*, 11 (4), 330–339, 2010.
23. Veljanoski Z., Pelivanoski P.: Lessening the leakage of water by reduction the pressure in the water supply systems. *Water management and hydraulic engineering. Proceeding of the VII International symposium on water management and hydraulic engineering*, 391–396 Poland, Gdańsk 2001.
24. Siwoń Z.: Problemy modelowania i eksploatacji systemów dystrybucji wody. *Zaopatrzenie w wodę, jakość i ochrona wód. IV Międzynarodowa konferencja, XVI Krajowa konferencja, Wydawnictwo PZITS Oddz. Wlkp.*, 735–754, Poznań 2000.

Modeling of water flow through 90 degree elbow installed on PEX-Al-PEX water supply pipeline

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Abstract

Minor losses in the modern flow installations, including water supply systems, constructed of new polymer materials may comprise a significant part of total pressure losses, even exceeding the friction losses in cases of the complex systems. Additionally, the minor losses occurring at joins of plastic pipes performed by heat fusion or mechanical fittings show higher values of minor loss coefficients than traditionally accepted values, usually based on the geometrical characteristics of the join. The above results probably from the complex construction of inner space of the join, reflecting the complicated shape of flow volume and causing the additional flow resistance. The method of numerical modeling based on Computational Fluid Dynamics (CFD) allows, beside determination of pressure loss for a studied type of fitting, the identification of factors triggering and influencing the flow resistance, such as flow velocity field or turbulent intensity distribution. This paper presents the results of modeling studies concerning water flow through the 90 degree elbow installed on PEX-Al-PEX of the nominal diameter 16 mm, allowing to determine the value of minor losses coefficient as well as determination of phenomena influencing the pressure drop. Our studies were performed with use of the commercial CFD modeling software Fluent 6.3, Ansys Inc. USA for the variable Reynolds number of range 5731–22868. The observed value of minor loss coefficient for the tested elbow, obtained by numerical calculations, was in the range of 9.5–10.78. The relations between resultant coefficient of minor pressure loss and Reynolds number as well as the water flow velocity field and distribution of turbulence intensity during water flow were observed. The presented model was validated by comparison of the obtained results to the results of laboratory measurements performed on the specially constructed laboratory installation. The empirical validation of our model should be treated as positively accomplished with R = 0.95, RMSE = 0,72, NRSME=0.09 and Nash-Sutcliffe's coefficient E = 0.83 observed.

Keywords

minor losses, polymer pipes, CFD, numerical modeling

1 Introduction

Precise and correct determination of pressure minor losses in not large but complex domestic installations of water supply and heating made from polymer pipelines, for which local pressure losses are assessed as significant part of total pressure losses (even up to 40–60%) may pose several serious problems (*Solter; Cisowska and Kotowski, 2006; Grajper and Smołka, 2010; Weinerowska-Bords, 2014*). Additionally, the reported studies showed than calculations of the minor pressure losses according to well known methodology, based in Poland on former PN-M-34034:1976 standard, commonly do not match the real values (*Grajper and Smołka, 2010; Siwiec et al., 2002; Cisowska and Kotowski, 2006; Strzelecka and Jeżowiecka-Kabsch, 2008, 2010; Widomski et al., 2012*). Calculations of minor losses for fittings and materials unknown in 1970s are based on minor loss coefficients provided by the producers. Unfortunately, the provided input data for total pressure losses calculations commonly do not reflect the possibility of installation of discussed element (fitting) on several possible pipelines materials, joined together by various possible techniques. Moreover, quite often input data for designing are divergent and do not include the fact that locations of pressure drop are installed very close one to another, like fittings and joins with pipe material.

The available standards, literature and technical guidelines, show usually constant values of coefficient of minor pressure drop, not related to Reynolds number but only sometimes to pipe diameter, for the 90 degree installation elbow, from 0.75 (*Pope, 1997*) or 0.8 (*Mott, 2014*), up to1.6 (*Pipelife*), 2,5–3.0 (*Kalenik, 2007*), 3.4 (*Uponor, 2012; Roth, 2012*).

The aim of this paper is to present the results of studies considering numerical and laboratory determination of Reynolds number dependant minor pressure loss coefficient for DN 16 90 degree elbow installed on PEX-Al-PEX domestic installation pipeline. Numerical modeling in this paper was applied to analyses of water flow velocity field and turbulence intensity distribution inside stream of water passing through the tested elbow, to identify the factors influencing the value of local pressure loss and coefficient of minor pressure loss.

2 Materials and Methods

Our studies covered numerical modeling and laboratory measurements of pressure loss and coefficient of minor losses for 90 deg. elbow installed on PEX-Al-PEX domestic water supply pipeline.

The DN 16 90 degree steel elbow used in our research was presented in Fig. 1. The applied fitting was installed in laboratory measurement installation constructed of DN 16 PEX-Al-PEX pipes of inner roughness $k=3\ 10^{-5}$m, according to scheme presented in Fig. 2.

Fig. 1. Picture of tested short DN 16 90 degree elbow

Laboratory measurements of pressure drop during water flow through the tested 90 degree elbow for the variable Reynolds number (i.e. variable volumetric flow rate of flow) were performed on specially constructed laboratory installation presented in Fig. 2.

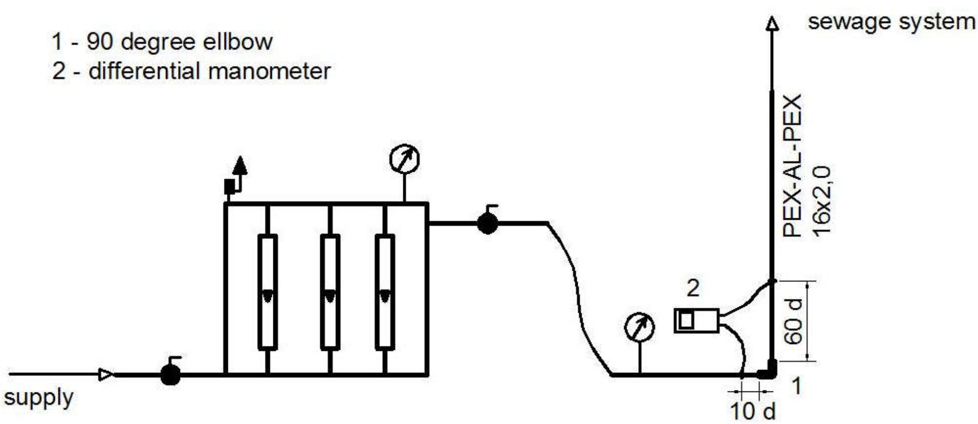

Fig. 2. Scheme of laboratory installation applied to pressure loss measurements

Volumetric rate of flow was measured by set of rotameters for water by Rotting, Germany and verified by the standard bucket method. Difference of pressure before and after studied elbow was measured by electronic differential manometer by Lutron Electronic of measurement range 0–10 mH_20 and accuracy ± 2%.

Laboratory measurements of pressure loss at tested 90 deg. elbow were performed for Reynolds number range 3143–51273 (volumetric flow rate 100 to 980dm^3 h^{-1}) and temperature of water in range of 15.6 15.7 C degrees. All measurements were duplicated to minimize possible errors.

Measured pressure loss was used as input data for calculation of coefficient of minor losses, according to transformed Bernoulli's equation:

$$Z = (\Delta h_s - \frac{u_2^2 - u_1^2}{2g} - \lambda_1 \frac{l_1}{d_1}\frac{u_1^2}{2g} - \lambda_2 \frac{l_2}{d_2}\frac{u_2^2}{2g})\frac{2g}{u_2^2} \tag{1}$$

where: ρ – density of water [kg/m^3], u – water flow velocity [m/s], h_s – measured pressure loss [mH_2O], g – gravity acceleration [m/s^2], λ – dimensionless friction factor [-], l – pipeline length [m], d – pipe diameter [m], Z – coefficient of minor pressure losses [-].

Value of friction factor for each applied Reynolds number was calculated according to formula by Colebrook - White:

$$\frac{1}{\sqrt{\lambda}} = -2\log\left[\frac{k}{3{,}7d} + \frac{2{,}51}{\mathrm{Re}\sqrt{\lambda}}\right] \tag{2}$$

where: Re – dimensionless Reynolds number, k – roughness of internal surface of the pipe.

Numerical modeling of water flow through was performed for the tested short 90 degree elbow of nominal diameter DN 16 and inner diameter 8 mm fitted to multilayered installation pipe PEX-Al-PEX 16x4 mm. The numerical simulations based on computational fluid dynamics (CFD) method were performed by computing software Fluent 6.3 included in Ansys 12.1, Ansys Inc., USA. Validation of the numerical model was based on measured results of laboratory experiment described above. The developed model reflected water body shape limited by the studied elbow and applied pipelines. The described model was consisting of 197407 nodes and 987297 elements of finite elements/volumes mesh (Fig. 3).

Numerical calculations of water flow through modeled piping installations performed for water of temperature from range 15.6–15.7 C degree, density of range 998.65–998.67 kg·m^{-3}, dynamic viscosity 0.001088–0.001091Pa·s and variable water flow rate. Numeric calculations were performed for inflow boundary conditions covering 12 values of mass flow from range 0.0294–0.2628 kg·s^{-1} which reflected Reynolds number 2865–25636 and water flow velocity 0.26–2.33 m·s^{-1}.

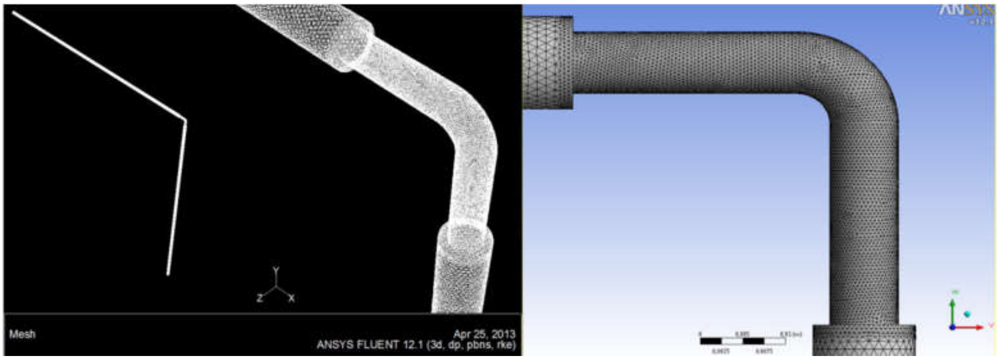

Fig. 3. Developed model of short DN 16 90 degree elbow installed on PEX-Al-PEX pipeline

Numerical calculation of water flow, as flow of viscous incompressible liquid, were based on the standard two-equation k-epsilon model of turbulence (*Lauder and Spalding, 1974; Comini and Del Giudice, 1985*).

The result of numerical calculations covered velocity vector values and components, water pressure distribution and dimensionless turbulent intensity (TI), understood as presented in Equation (*PN-M-34034:1976; Shirazi et al., 2012*);

$$TI = \frac{\sqrt{u'}}{\bar{u}} \qquad (3)$$

where: u' – value of turbulent flow velocity fluctuation [$m \cdot s^{-1}$], $\bar{u}$ – mean value of velocity of flow [$m \cdot s^{-1}$].

The turbulent intensity for fully developed turbulent flow was reported as equal to value of 5% (*Zamora et al., 2008; Minkowycz et al., 2009*). The modeled coefficient of local losses was calculated according to Equ. 1.

3 *Results and Discussion*

Results of modeled and measured during laboratory researches values of pressure loss in accordance to variable Reynolds number are presented in Fig. 4.

Fig. 4. shows clear increase of pressure loss in relation to increase of Reynolds number, thus in relation of increase of flow velocity. For the lowest applied values of Re equal approx. to 2865 modeled and measured values of pressure loss varied between 1.81–18.86 kPa. Increase of Reynolds number to the maximum applied value, i.e. Re=25636 resulted in modeled and measured pressure loss equal to approx. 32 and 29 kPa, respectively. The two fitted power curves show good fit, representing coefficient of determination for p=0.05 R2 equal to 0.989 for both cases.

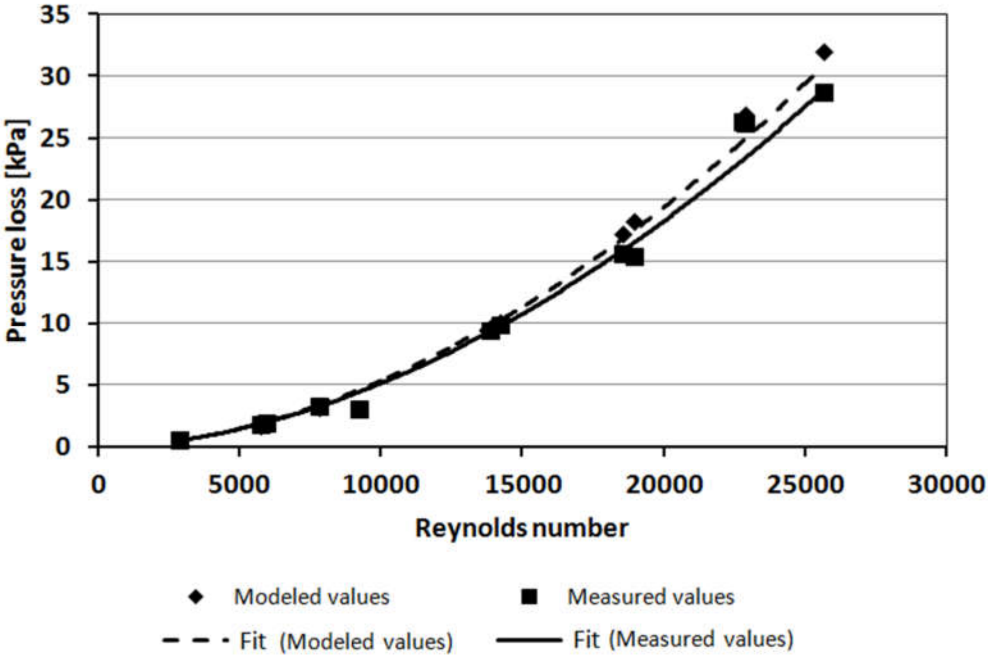

Fig. 4. Results of modeled and measured pressure loss for 90 deg elbow

Fig. 5. shows values of minor losses coefficient calculated for values of pressure loss obtained from numerical modeling and laboratory measurements. The decreasing relation of minor loss coefficient to Reynolds value was observed. The maximum values of minor loss coefficient were observed for the lowest applied Reynolds number, then contrary, the lowest coefficients were obtained for the highest values of Re number. Thus, the maximum calculated values of minor loss coefficient were between 14.17–15.56, while the minimal were 8.24–9.50. The mean values of minor loss coefficient for modeled and measured pressure loss were 15.56 and 14.17, respectively.

To better understand flow phenomena occurring during water flow through three different variants of modeling calculation results are going to be analyzed.

Fig. 6. shows velocity magnitude (in $m \cdot s^{-1}$) distribution for three cases of modeled water flow through the DN 16 90 deg elbow.

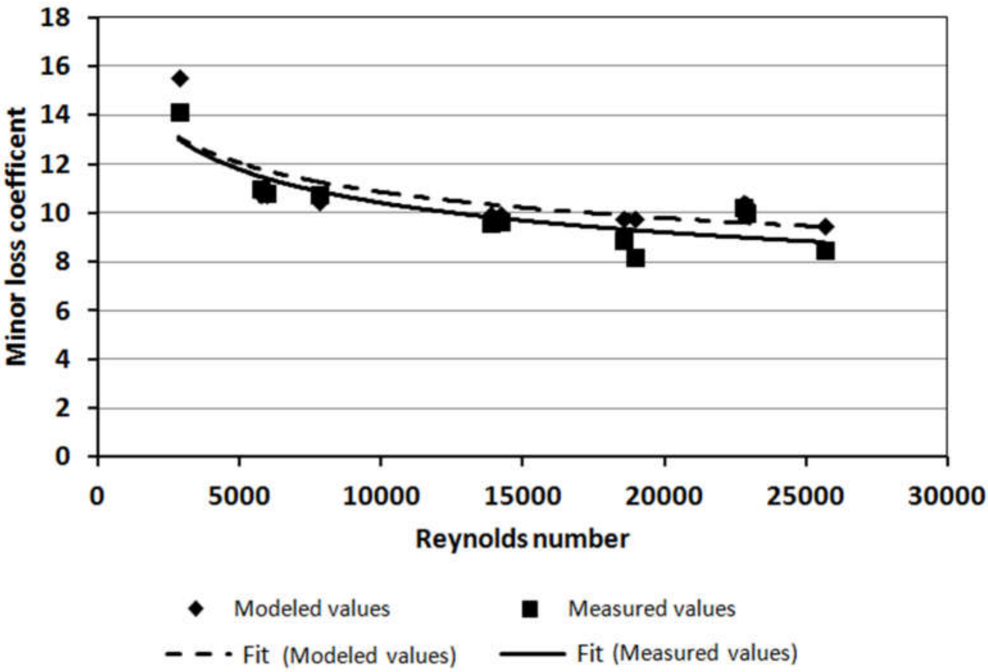

Fig. 5. Minor loss coefficient for modeled and measured pressure loss on 90 degree elbow

It is clearly visible in Fig. 6. that in all studied cases velocity field distribution, influenced by flow 3D water body is quite similar but values of velocity field are different. For the first case, with inflow velocity equal approx. 0.5 $m \cdot s^{-1}$, the maximum observed velocity of flow through the tested elbow, resultant from contraction of the stream, was equal to 1.65 $m \cdot s^{-1}$. For the second variant, with inflow speed at boundary equal to approx. 1.3 $m \cdot s^{-1}$, the maximum velocity of flow at the contraction zone reached the value of 3.86 $m \cdot s^{-1}$, while for the last discussed variant with inflow, undisturbed velocity equal to approx. 2.1 $m \cdot s^{-1}$, the maximum value of velocity field was at the level of 3.3 $m \cdot s^{-1}$. Thus, the clear relation between increase of flow velocity caused by contraction and bending of the stream and momentum changes resulting in increased mechanical energy and pressure loss (Fig. 6) are visible.

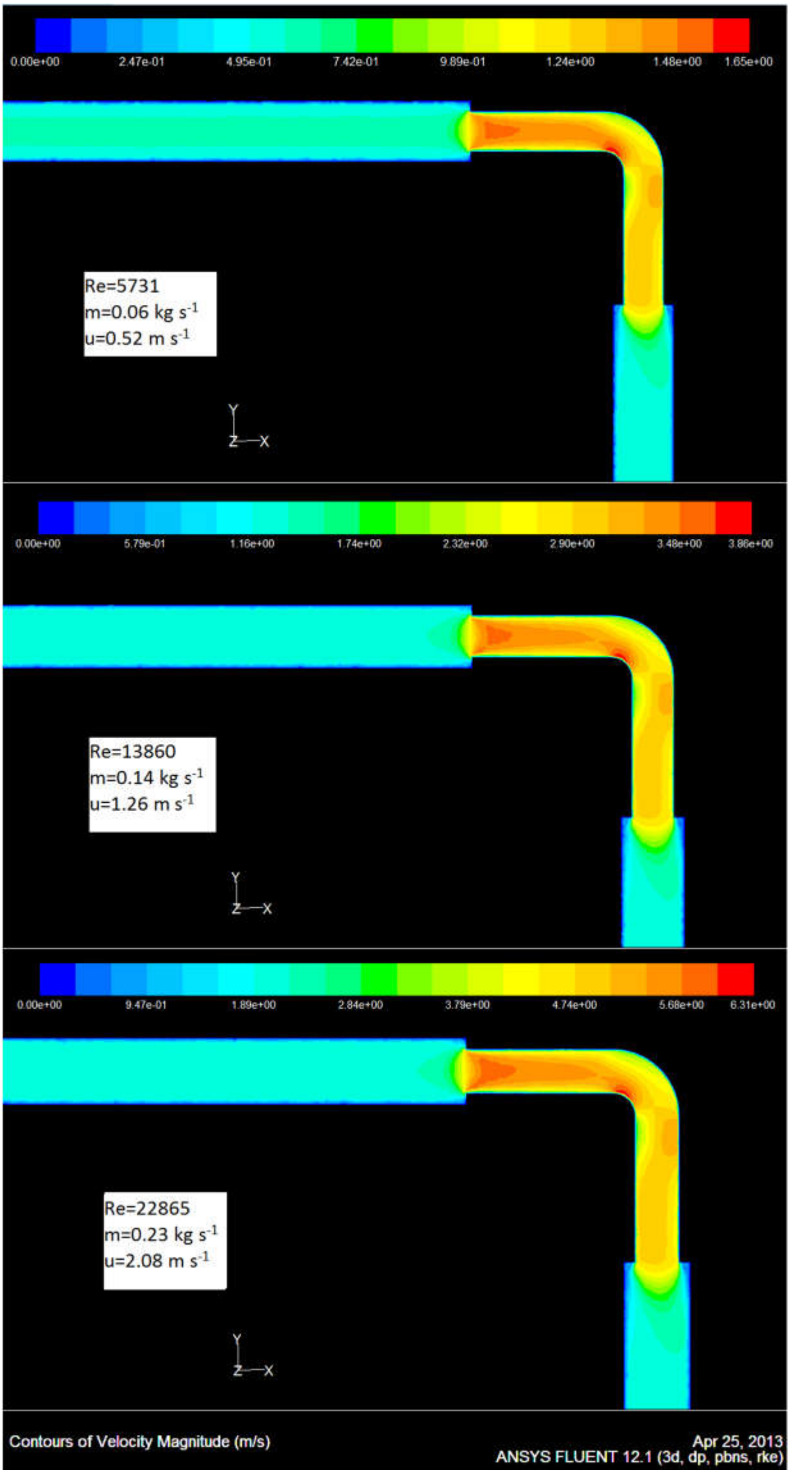

Fig.6. Velocity magnitude distribution for three variants of calculations.

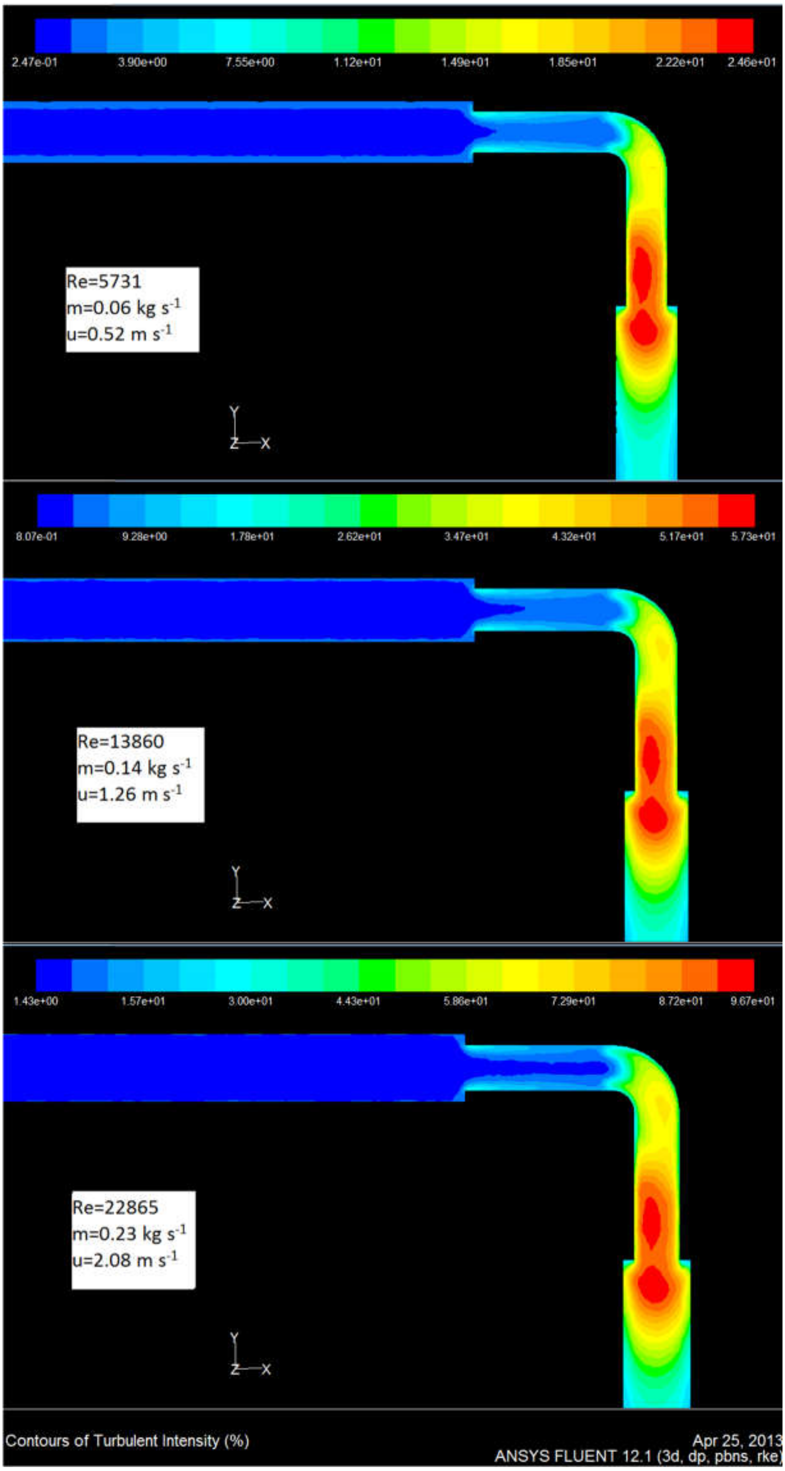

Fig. 7. Spatial distribution of turbulent intensity for three selected variants of calculations

Fig. 7. shows spatial distribution of dimensionless turbulent intensity (TI), presented in %, for all the selected three discussed variants of numerical modeling. In all presented cases the influence of variable shape of water body, resulting from inner shape of elbow and its fittings, is clearly visible. The spatial arrangement of additional turbulences caused by changes of flow geometry and contraction of the stream is similar in all cases. However, it's also visible that the reached value of turbulent intensity was in all cases different. For the lowest inflow velocity and Reynolds number (0.52 $m \cdot s^{-1}$, approx. 5700, respectively, TI behind stream contraction zone reached value of 25%, five times greater than for fully developed turbulent flow. In case of the second presented variant, for boundary velocity of flow equal to 1.3 $m \cdot s^{-1}$, and Reynolds number 13860 turbulent intensity reached value 57%. The highest maximum turbulence intensity value equal to approx. 97% was observed in modeling results for the third flow variant, with inflow boundary velocity equal to 2.1 $m \cdot s^{-1}$ and Reynolds number Re = 22865. Such high increase of turbulences of flow, quantified by TI, clearly explains the value of measured and modeled pressure losses for 90 degree DN 16 elbow during water flow rate with significantly high, as for domestic installations, volumetric flow rate.

Figs. 8, 9 and 10 present velocity vectors (magnitude value and directions) for discussed variants of simulation. In all tested cases there are visible changes of velocity vectors values and direction caused by changes of inner shape of tested fitting and pipelines. The stationary vortices zones are visible in all cases, at sudden contraction of pipe diameter at the beginning of the modeled fitting and at the sudden pipe expansion at the outflow from the 90 degree elbow. Thus, we can see that the value of pressure loss and the minor pressure loss coefficient are resulting from the subsequent phenomena causing changes of liquid momentum such as sudden contraction, 90 degree bend with boundary layer separation and resultant contraction, and finally sudden stream extraction. All the above mentioned phenomena, placed very close, one to another, result in significant pressure drop for domestic installation DN 16 90 deg elbow.

The calculated coefficient of minor losses was equal to 10.77, 9.95 and 10.37 for the first, second and third discussed variants, respectively.

The developed model was validated by comparison of the obtained results of numerical modeling to values measured during laboratory researches. The root square mean error for minor loss coefficient was equal to 0.72, normalized root square mean error reached the value of 0.09, coefficient of correlation R=0.95 and Nash-Sutcliffe coefficient E=0.83 show good agreement between compared values.

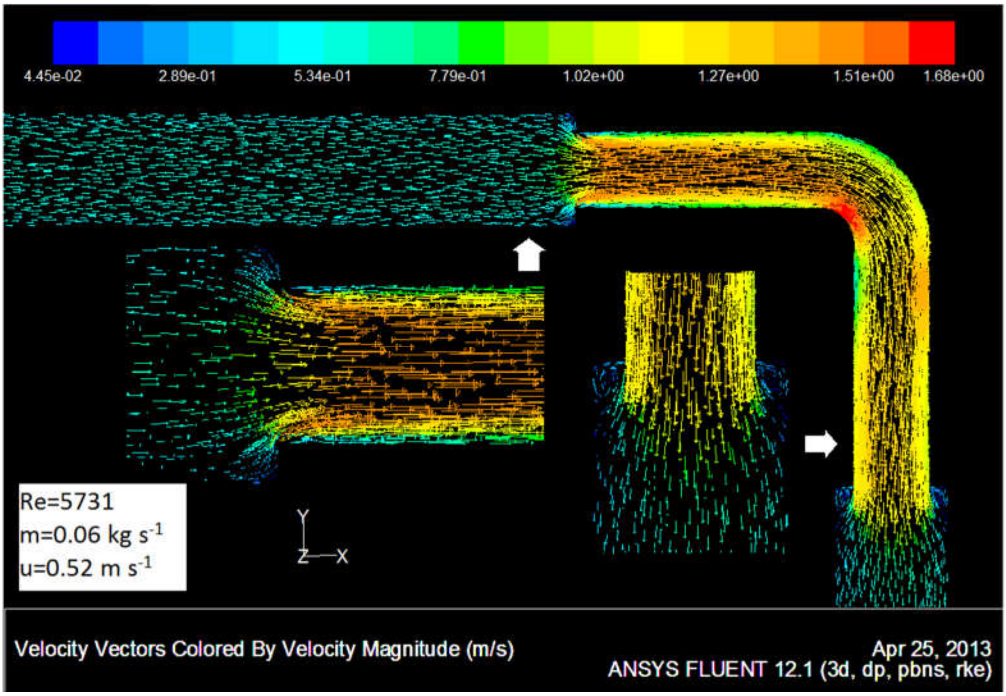

Fig. 8. Velocity vectors for inflow boundary Re=5731

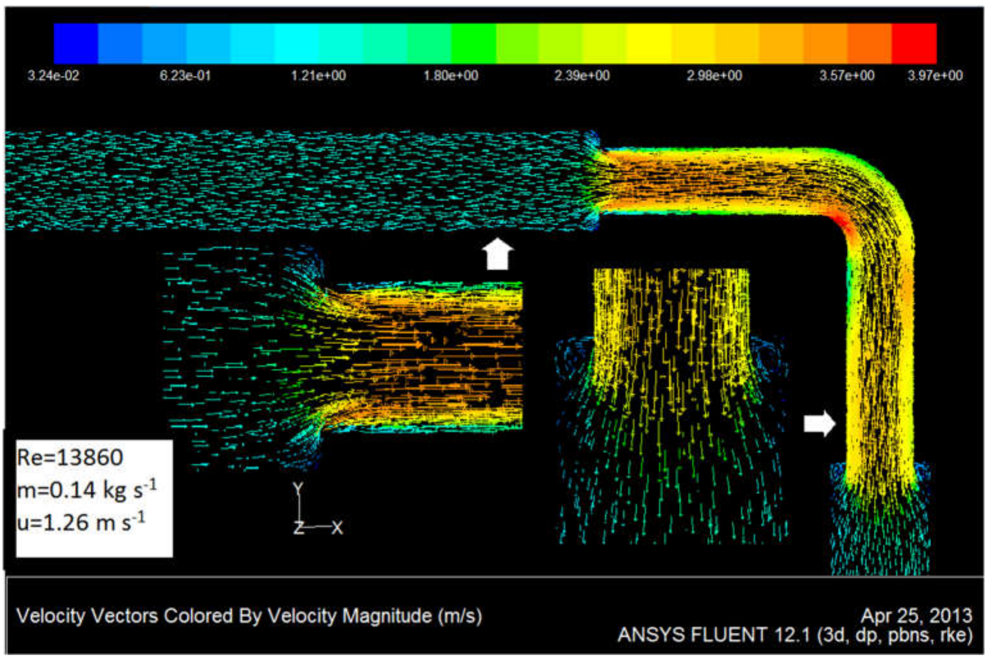

Fig. 9. Velocity vectors for inflow boundary Re=13860

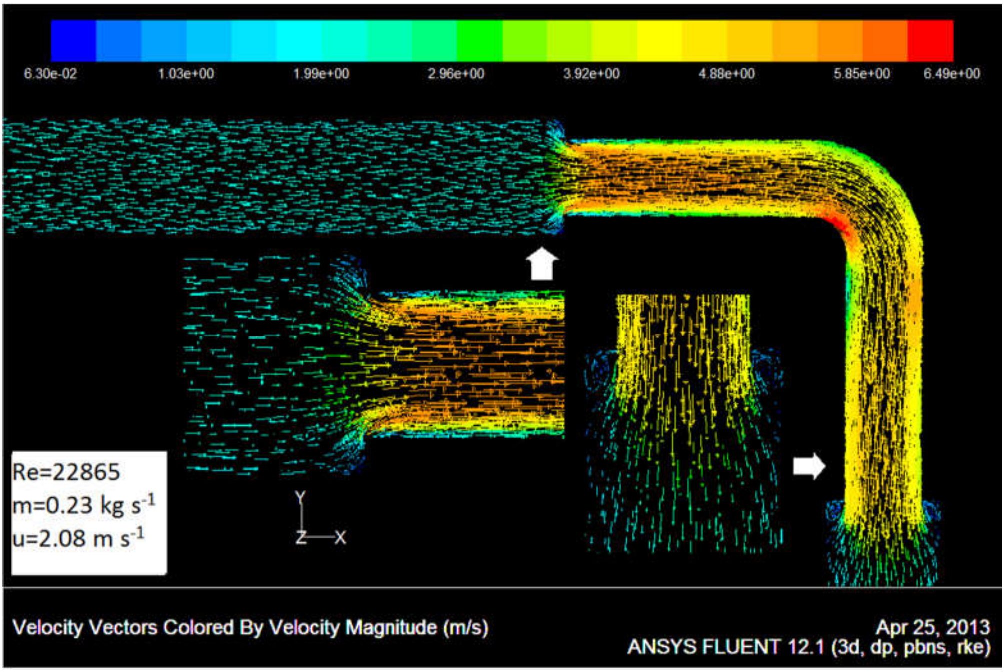

Fig. 10. Velocity vectors for inflow boundary Re=22865

4 *Summary and Conclusions*

The observed value of minor loss coefficient for the tested elbow, obtained by numerical calculations, was in the range of 9.5–15.56. While literature and technical guidelines, as it was mentioned before, show values significantly lower, up to1.6 (*Pipelifie*), 2,5–3.0 (*Kalenik, 2007*), 3.4 (*Uponor, 2012; Roth 2012*). The visible difference may be resultant from the fact that for the purpose of this paper, the DN 16 domestic installation 90 deg elbow was tested together with pipe fittings, allowing connection between the elbow and pipelines. Our studies suggest that application of minor loss coefficients taken directly from technical literature, without respect to type and quality of pile-fitting connection may lead to underestimation of minor pressure losses for the whole installation.

The relations between resultant coefficient of minor pressure loss and Reynolds number as well as the water flow velocity field and distribution of turbulence intensity during water flow were observed. The higher values of local flow velocity at stream contraction zones as well as the higher turbulence intensity, the higher observed pressure loss for the tested elbow.

The presented model was positively validated by comparison of the obtained results to the results of laboratory measurements performed on the specially constructed laboratory installation.

References

1. Cisowska I., Kotowski A.: Straty ciśnienia w układach kształtek z polipropylenu. *Gaz, Woda i Technika Sanitarna*, 10, 2004.
2. Cisowska I., Kotowski A.: Studies of hydraulic resistance in polypropylene pipes and pipe fittings. *Fund. of Civil and Environmental Eng.*, 8, 37–57, 2006.
3. Grajper P., Smołka J.: Eksperymentalne i numeryczne określenie miejscowych strat ciśnienia w kolanach 90° instalacji wodociągowych. *Gaz, Woda i Technika Sanitarna*, 7–8, 2010.
4. Kalenik M.: Niekonwencjonalne systemy kanalizacji. Wydawnictwo SGGW. Wydanie pierwsze - Warszawa 2007.
5. Minkowycz W.J., Abraham, J.P., Sparrow, E.M.: Numerical simulation of laminar breakdown and subsequent intermittent and turbulent flow in parallel-plate channels: Effects of inlet velocity profile and turbulence intensity. *International Journal of Heat and Mass Transfer*, 52, 2009.
6. Mott R.: Applied Fluid Mechanics. Prentice Hall. Upper Saddle River. New Jersey 2014.
7. Pipelife, System do wody użytkowej i ogrzewania Radopress.
8. PN-M-34034:1976. Rurociągi – zasady obliczeń strat ciśnienia.
9. Pope E.J.: Rules of Thumb for Mechanical Engineers: A Manual of Quick, Accurate Solutions to Everyday Mechanical Engineering Problems. Gulf Professional Publishing. Huston. Texas 1997.
10. Roth, 2012, Katalog techniczny, Systemy instalacji rurowych.
11. Shirazi N.T., Azizyan, G.R., Akbari, G.H.: CFD analysis of the ball valve performance in presence of cavitation. *Life Science Journal*, 9 (4), 1460–1467, 2012.
12. Siwiec T., Morawski D., Karaban G.: Eksperymentalne badania oporów hydraulicznych w zgrzewanych kształtkach z tworzyw sztucznych. *Gaz, Woda i Technika Sanitarna,* 2, 2002.
13. Strzelecka K., Jeżowiecka-Kabsch, K.: Rzeczywiste wartości współczynnika oporów miejscowych podczas przepływu wody przez skokowe rozszerzenie rury. *Ochrona Środowiska*, 30 (2), 2008.
14. Strzelecka K., Jeżowiecka-Kabsch K.: Rzeczywiste wartości współczynnika strat miejscowych podczas przepływu wody przez nagłe rozszerzenie rury. *Ochrona Środowiska*, 32 (1), 2010.
15. Uponor, Instalacje Ponor, Poradnik techniczny, 2012.
16. Weinerowska-Bords K.: Eksperymentalna analiza współczynników oporów lokalnych dla wybranych kształtek i złączek w systemach rur wielowarstwowych. *Instal*, 6, 42–49, 2014.
17. Widomski M. K., Musz A., Iwanek M.: Straty ciśnienia na zaworze antyskażeniowym - badania laboratoryjne i modelowe. *Gaz, woda i technika sanitarna,* 9, 380–385, 2012.
18. Zamora B., Kaiser A. S., Viedma A.: On the effects of Rayleigh number and inlet turbulance intensity upon the buoyancy-induced mass flow rate in sloping and convergent channels. *International Journal of Heat and Mass Transfer* 51: 4985–5000, 2008.