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SELECTION OF THE MOST EFFECTIVE BIOLOGICAL EARLY WARNING SYSTEM, BASED ON AHP AND REMBRANDT ANALYSIS

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ABSTRACT

In paper, the ability to use of the biological early warning systems, in tap water quality biomonitoring was analyzed, based on multiple-criteria decision analysis. Five groups of organisms (invertebrates, fishes, algae, fungi and bacteria) were analyzed for the sensitivity to disturbance, the area of use, the amount of detected components, the rate of reaction and the data interpretation. Both analyzes revealed, that invertebrates are the most sensitive bioindicators (49% AHP, 29% Rembrandt). The other organisms which are useful in BEWS systems are algae and fishes. More problematic may be systems based on fungi and bacteria.Both analysis Rembrandt, as well as analytic hierarchy process(AHP) have indicated the rate of reaction as the most important factor in BEWS. All of BEWS systems are focused on reduce the time required to obtain the information about pollution presence, because the standard monitoring of tap water quality, based on physical and chemical methods, are usually time consuming.

Keywords: AHP, Rembrandt, biomonitoring, biological early warning systems

INTRODUCTION

Chemical analyses are indispensable for the production of safe drinking water. They facilitate detection of biological as well as chemical pollution, and in case of emergency, they make it possible to undertake treatment action. A lack of continuous monitoring in time is the biggest limitation (Bae and Park 2014). Due to the growing number of unidentified pollutants, in order to make an appropriate assessment of their impact on living organisms, biological monitoring is additionally used.

Two types of biomonitoring can be distinguished: active and passive. Passive biomonitoring focuses on the observation of living organisms in their natural environment. Active biomonitoring consists in placing living organisms within the designated research area and observing their behaviour (Traczewska 2008). Correct interpretation of behavioural changes is significant in context of tap water quality monitoring.

The factors, which are harmful to human health, and which are present in drinking water, can be divided into microbiological and chemical elements. The chemical pollutants, in contrast to microbiological ones, usually do not cause acute effects. What is problematic is their ability to exert harmful effect after long the actual period of their consumption. This is particularly true of heavy metals and carcinogenic substances (Wojtyła-Buciora and Marcinkowski 2010). Water pollutants in water supply network can be caused by sources contamination, by exploitation problems, or by secondary water contamination in pipes (Szpak and Tchórzewska-Cieślak 2015). For that reason, water quality monitoring is one of the most important parts of water distribution process.

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In the present work, we have analysed the possibility of using biological early warning systems in tap water quality biomonitoring, based on multiple-criteria decision analysis (MCDM).

The MCDM analysis makes it possible to take account of many factors and their interconnections. Based on these, the selection of the most favourable method of water biomonitoring is possible.

MATERIAL AND METHODS

AHP and Rembrandt methods of multi-criteria decision

Discrete methods of multi-criteria decision support, developed rapidly in recent years can be used to analyze the decision-making in various fields of science (Trzaskalik 2014).

In the literature can be find many examples of the use of the basic method of multi-criteria AHP. In paper Vahdani et al. (2010) model has been applied to a vendor selection process of a firm working in the field of rail transportation. Triantaphyllou (2000) describes the problem of choosing the best method of multiple-choices, concentrate on methods such as WSM, WPM, AHP, revised AHP, ELECTRE, TOPSIS. Lootsma (2007) described basis analysis multiple with using SMART and AHP method. Bolloju (2001) models AHP representing employment preferences of two subjects with of the 70 AHP models revealed that a wide variety of factors.

The REMBRANDT method has been designed to address three criticized features of AHP. In this method, the scale Saaty's is replaced by a logarithmic scale. Determining the value of their solutions by Perron-Frobenius is replaced with the logarithmic least squares estimation (Trzaskalik 2014). The first issue described by Lootsma was the numerical scale for verbal comparative judgment Olson (1995).

The Decision, based on comparative judgement of C_j to C_k, was captured on a category scale to restrict the range of possible verbal responses. This is converted into an integer-valued gradation index d_{jkd} according to the scale in Table 1 (Van den Honert and Lootsma 2000):

The ratio matrix in REMBRANDT for criteria is transformed through the operator $e^{y \cdot \delta(jk)}$ to generate the set of values transformed to the logarithmic scale. Lootsma considers two alternative scales y to express preferences. For calculating the weight of criteria, $y = \ln 2 \approx 0.347$ is used. For calculating the weight of alternatives on each criterion, $y = \ln 2 \approx 0.693$ is used. Notes that the geometric means of row elements of such a matrix yields the solution minimizing the sum of squared errors.This solution is normalized by product. It is a simple matter to normalize by sum, simply dividing eachelement by the total (Olson et al. 1995, Van den Honert and Lootsma 2000, Modiri et al. 2010).

Table 1. Comparative judgment hierarchy (Van den Honert, Lootsma, 2000)

No.	Comparative judgment	Gradation index d_{jkd}	Saaty ratio
1.	Very strong preference for C_k over C_j	–8	1/9
2.	Strong preference for C_k over C_j	–6	1/7
3.	Definite preferences for C_k over C_j	–4	1/5
4.	Weak preference for C_k over C_j	–2	1/3
5.	Indifference between for C_k over C_j	0	1
6.	Weak preference for C_k over C_j	2	3
7.	Definite preferences for C_k over C_j	4	5
8.	Strong preference for C_k over C_j	6	7
9.	Very strong preference for C_k over C_j	8	9

Living organisms used in biotests

Water quality biomonitoring based onbioindication is applied for many years (Bea and Park, 2014). Precise diagnosis of specific behavior represents an organism's responses to the environmental changes, contributed to increase the popularity of biological early warning systems (BEWSs).

Systems are more sensitive and precise than physicochemical sensors. They allow to obtain information about various pollutions in real-time (heavy metal, organic and inorganic components, pesticide, herbicide and antibiotics) (Kramer and Foekema 2000, Gu et al. 2004, Zurita et al. 2007, Storey et al. 2011, Traczewska 2011, Woutersen et al. 2011, Bea and Park 2014, Jia i Ionescu 2015, Häder and Erzinger 2017). The tools used to evaluate behavior are inexpensive what makes them both more practical and economical than chemical methods.

Continuous monitoring of tap water quality resulted in the development of commercial systems based on bioindicators. Biological early warning systems evaluate the quality of water based on the reaction of invertebrates (Kramer and Foekema 2000, Gu et al. 2004, Storey et al. 2011, Traczewska 2011, Bea and Park 2014, Häder and Erzinger 2017), algae (Stevenson and Smol 2003, Gu et al. 2004, Allan et al. 2006, Zurita et al. 2007, Zhou et al. 2008, Storey et al. 2011, Traczewska 2011), fish (Van der Schalie et al. 2001, Gu et al. 2004, Allan et al. 2006, Gerhardt et al. 2006, Storey et al. 2011, Traczewska 2011, Bea and Park 2014), fungi (Välimaa et al. 2008, Traczewska 2011, Rumlova and Dolezalova 2012, Wachowska and Stasiulewicz--Paluch 2016) and bacteria (Zurita et al. 2007, Storey et al. 2011, Traczewska 2011, Woutersen et al. 2011, Jia and Ionescu 2015).

Invertebrates

The most popular invertebrates used in those systems are Daphnia, Gammarus, Rotifers as well as Gastropods and Clams. Impact of the pollutants on to the species is evaluated for mortality, reproduction, swimming behavior, valve opening/closing etc. The possibility of adaptation to the various environments allows to assess the quality of the fresh water (including tap water), saltwater and wastewater (Kramer and Foekema 2000, Traczewska 2011). Real-time monitoring systems based usually on behavioral reaction of Daphne (DaphTox II, Multi-DaphTrack, Daphniatox etc.) or bivalves (The Mooselmonitor, The Dreissena Monitor, Symbio etc.). Reaction rate depends on concentration and kind of substance. The minimum time to obtain the changes of behavior is 2 minutes (Häder and Erzinger 2017). High sensitivity of invertebrates can result the reaction on the other factors like changes of temperature, pH, salinity or chlorine, which are not danger for human health. Predisposition to detect heavy metals, pesticides, herbicides, chemical, organic and inorganic substances, as well as uncomplicated interpretation of reactions makes invertebrates more effective bioindicators than other organisms (Gu et al. 2004, Storey et al. 2011).

Algae

Assessment of water quality based on aquatic plants entails a significant amount of time needed for their growth (Traczewska 2011). Real-time detection of the pollutants is possible solely with algae monitoring. Usually chlorophytes are used. Similarly to invertebrates, allow to assess quality of fresh water, saltwater and wastewater (Allan et al. 2006, Zhou et al. 2008). Popular system based on chlorophytes is Algae Toximeter. The instrument compares the effects of toxins on the one part of algae to the another part kept in clean water with known parameters. The principle of operation based on the determination of the fluorescence spectrum and oxygen demand. To get the response, 10 minute time is required (Mons 2008). Algae are sensitive to change of irradiation and substances, which are not danger for human health.In addition, the cultivation of the identical cultures of the test organisms is difficult (Stevenson and Smol 2003, Gu et al. 2004, Zurita et al. 2007, Storey et al. 2011).

Fish

Fishes were one of the first organisms used in BEWS (Bea and Park 2014). Rainbow trout, zebrafishes and guppies are usually used in biomonitoring systems. The individual species and their various form are able to detect pollutions in fresh water, saltwater and wastewater (Van der Schalie et al. 2001, Allan et al. 2006). Systems like Fish Toximeter, ToxProtect, The Bio-Sensor measures the changes of swimming speed and/or muscles activity (gill movements). Fishes are able to detect from 0,003 to 100 ppm of pollution (heavy metals, chemical compounds, pesticides) (Traczewska 2011). To get the response, about 17 minute time is required after the toxic substances occurred. Sensitivity of fishes can result in the reaction on the other factors like changes of temperature, pH, salinity or chlorine. The breeding and the development of special procedures to identify specific behavioral changes, require considerable experience. In addition, research and testing on vertebrate animals must obtain approval from The Animal Experiments Committee (Gu et al. 2004, Gerhardt et al. 2006, Storey et al. 2011).

Fungi

Fungi are rarely used in biomonitoring compared to the other organisms. Inhibition of growth and changes in cells shape of S. cerevisiae for toxic substances are usually measured (Rumlova and Dolezalova

2012, Wachowska and Stasiulewicz-Paluch 2016). The main limitation is the possibility of using only in freshwater. Fungi are sensitive for pH and salinity changes. Pollution presence observation is possible after 2 hours of exposition (Välimaa et al. 2008). Despite the limitations, Rumlova and Dolezalova proved that fungi are more usefull to obtain the information about presence atropine, fenitrotion and potassium cyanide in the water than popular biotests based on bacteria V. fisheri or invertebrates D. magna (Rumlova and Dolezalova 2012).

Bacteria

Bacteria has been used in eco-toxicological research since 80's measuring their level of oxygen demand, nitrification process, grow and luminescence (Bea and Park 2014).The advantage of research with V. fischeri, P. fluorescens, Spirillum sp. is their non-invasive, low cost, speed and repeatability. Bacteria are used to assessment of freshwater, tap water (excluding V. fischeri) and wastewater quality (D'souza 2001). The wide range of applications and ease of research, lead to increased numbers of water quality control systems, based on the bacteria reaction (RODTOX 2000, Amtox, Microtox, TOXcontrol itd.). Organisms are sensitive on presence of heavy metals, organic compounds, pesticide and antibiotics in the water. Response time, required to obtain results does not exceed 30 minute (Zurita et al. 2007, Storey et al. 2011, Woutersen et al. 2011, Jia and Ionescu 2015). The main limitations of systems based on bacteria reaction are temperature, salinity and sensitivity to substances which are not danger for human health.

AHP and Rembrandt tree structure

The tree structure was prepared on the basis of the literature review. Based on it, the most useful of the proposed methods of water quality real-time monitoring was chosen (see: Fig. 1). The advantage of the AHP and Rembrandt analysis is investigate the relation between the quantities and qualities parameters which are not mutually connected, at the same time.

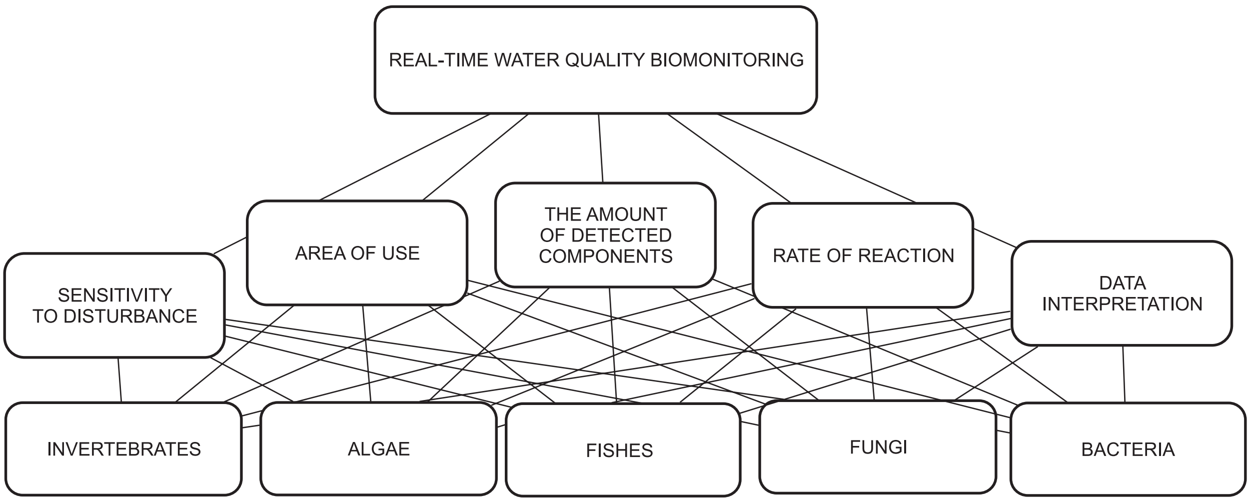

Fig. 1. Tree structure

RESULT AND DISCUSSION

Five groups of life organisms, used in biological early warning system were analyzed.Sensitivity to disturbance, area of use, the amount of detected components, rate of reaction and data interpretation were checked by the criteria-based assessment.

The previously mentioned information from the literature were used to compare the differences between the groups. Both analysis Rembrandt, as well as AHP have indicated the rate of reaction as the most important factor in BEWS (see: Fig. 2). Most of BEWS systems are focused on reducing the time required to obtain the information about pollution presence, because the standard monitoring of tap water quality, based on physical and chemical methods, are usually time consuming. The standard toxicology tests, as well as physicochemical sensors, cannot provide the comprehensive water safety in real-time (Van der Schalie et al. 2001, Bea and Park 2014). Searching for organisms or technologies which allow to minimize the rate of reaction in BEWSs is the main aim of research papers topics (Rumlova and Dolezalova 2012).

The other factor which is indispensable in BEWSs is the amount of detected components. The validity of research related to the amount of contamination is confirmed in Zhou, Van der Schalie or D'souza works (D'souza 2001, Van der Schalie et al. 2001, Zhou et al. 2008). The standard monitoring based on chemical analyses do not allow for continuous pollution control and the water quality cannot be always guarantied. One of the biggest limitation of biological systems was the inability to distinguish pollution. However, Bea and Park as well as Rumlova and Dolezalova researches point that used a few organisms in the same time, as one multispecies monitor make more possible detection and recognize kind of compound (Rumlova and Dolezalova 2012, Bea and Park 2014).

For the other criteria the divergent results were obtained. The third criteria which was important in Rembrandt analysis was the sensitivity to disturbance (13%), while in the case of AHP analysis it was the area of use. In both cases, the data interpretation was the least important criterion. Possibility to create a false alarms is the second important limitation of the BEWSs (Bea and Park 2014). Sensitivity to temperature, pH or salinity changes occur in most of analyzed organisms group. Furthermore, part of organisms are more sensitive to low concentrations of the substance. Algae and fungi can detect the concentration of some substances, which are not danger for human health. Possibility to mark the response threshold in all of bioindicators groups is required to eliminate too sensitive organisms.

All of mentioned systems has wide area of use. Most of them are able to detect pollution in tap water after purification. It's important in case of requirement to providing good water quality, regardless of the period (Kramer and Foekema 2000, Gu et al. 2004, Storey et al. 2011, Traczewska 2011, Bea and Park 2014, Häder and Erzinger 2017). The biggest advantage of systems is possibility to use them in surface water. It is important in the case of water contamination to identify the pollution source. The least remark in the literature devoted to the data interpretation. It's more subjective than the other criteria (Stevenson and Smol 2003, Gu et al. 2004, Storey et al. 2011). In paper focused on possibility to detection of contamination based on visual observation.

For all analyzed criteria, the groups of mentioned organisms were compared with each other. In case of the reaction rate as well as the detected components amount, the highest values were obtained to invertebrates. A little more time was needed to observe the changes of behavior in case of algae systems. With

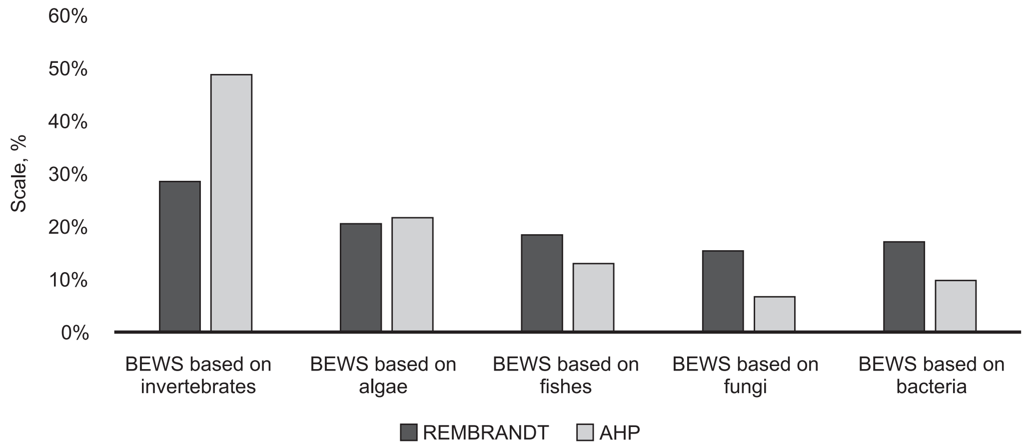

Fig. 2. Result of REMBRANDT and AHP analysis of criterial

the amount of detected components were demonstrated, that fishes can be also used in biomonitoring. The end result of AHP (49%) and Rembrandt (29%) analysis has demonstrated that invertebrates are the most useful organisms in biological early warning systems. They are characterized by one of the faster response to occuring contaminants, as well as a wide range of substances detected. The invertebrates are sensitive to some disturbance, but the area of their use include the largest number of environments. Other positions went to systems based on reaction of algae (AHP 22%, Rembrandt 21%), fishes (AHP 13%, Rembrandt 18%), bacteria (AHP 10%, Rembrandt 17%) and fungi (AHP 7%, Rembrandt 15%) (see: Fig. 2).

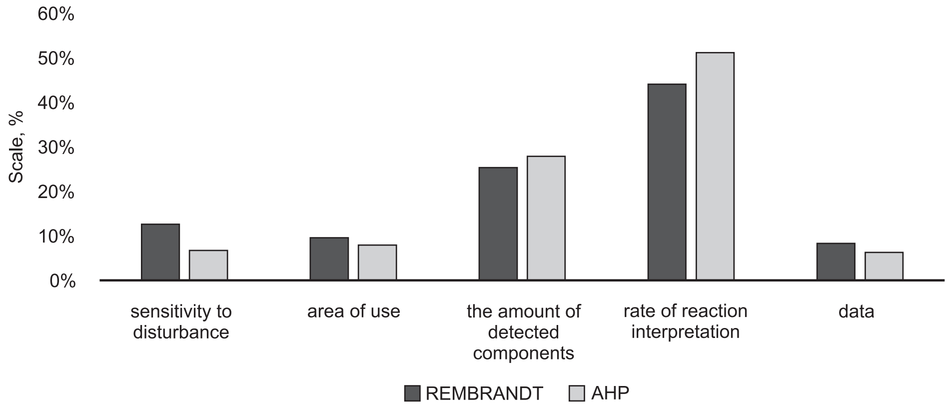

Fig. 3. Result of REMBRANDT and AHP analysis of organisms

CONCLUSION

Biomonitoring is essential for the identification of contaminants, for the protection of human health, for improving water quality, and for preventing its degradation. Changes in behaviour provide information about the individual and community-level effects caused by the contaminants that occur in water. However behavioural monitoring is hard to estimate objectively, and it is notoriously difficult to interpret behavioural data. Non-linearity of behaviours, variation in individual behaviour, and the large amounts of data obtained by continuous monitoring constitute the biggest limitations of these systems. Considering those limitations, choosing the most effective organisms for water quality biomonitoring can be difficult.

In order to solve the stated problems, in the present paper we have compared the use of Rembrandt with AHP analysis in group selection. Evaluation carried out using these the two systems is nearly identical, with the exception that the scales have different numerical values assigned. Rembrandt, as well as AHP, are well suited to group decisions. The primary benefit is the fact that differences of opinions are easy to identify. One of the procedural differences between the two methods is the calculation of impact scores. Based on the data from the Rembrandt analysis (the geometric mean) and the AHP analysis (the arithmetic mean), the same recommended solution was obtained, albeit with different values.

Based on the analyses that we have carried out, invertebrate organisms seemed to be one of the most sensitive bioindicators. Their behaviour was easy to interpret, and to observe. The response to the occurrence of contaminants can be measured by monitoring valve gap, or changes in shell opening. Moreover, the stress induced by organic solvents can also affect the frequency of opening and closing. On the other hand, it has not been possible to describe kind of pollutants with other groups of organisms as bioindicators.

In conclusion, it is possible to compare only stimuli in a limited range, where their perception is sensitive enough to make distinctions. The range should not be overly wide. When the range is too wide, then some elements that are close together tend to be summarily lumped together. It is well known that when applied to physical phenomena beyond our ability to perceive or respond to, the scale would fail.

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WYBÓR NAJBARDZIEJ UŻYTECZNYCH BIOLOGICZNYCH SYSTEMÓW WCZESNEGO OSTRZEGANIA, Z WYKORZYSTANIEM METOD AHP I REMBRANDT

ABSTRAKT

W artykule analizowano możliwość wykorzystania w wodzie wodociągowej biologicznego systemu wczesnego ostrzegania, bazując na wielokryterialnej metodzie podejmowania decyzji. Sprawdzono grupę pięciu organizmów (bezkręgowców, ryb, glonów, grzybów i bakterii) pod kątem wrażliwości na zakłócenia, obszar zastosowania, ilości wykrywanych zanieczyszczeń, prędkości reakcji oraz sposobu interpretacji danych. Na podstawie przeprowadzonych analiz wykazano, że bezkręgowce są najbardziej wrażliwymi bioindykatorami (49% AHP, 29% Rembrandt). Pozostałymi organizmami użytecznymi w biologicznych systemach wczesnego ostrzegania są ryby i glony. Bardziej problematyczne mogą być systemy oparte na reakcji grzybów i bakterii. Zarówno Rembrandt, jak i AHP wykazały, że prędkość reakcji organizmów jest najważniejszym czynnikiem decydującym o skuteczności działania systemów. Rolą wszystkich biologicznych systemów wczesnego ostrzegania jest skrócenie czasu uzyskania informacji na temat występowania potencjalnych zagrożeń w wodzie, ponieważ standardowe metody monitoringu oparte na analizach fizycznych i chemicznych są zazwyczaj bardziej czasochłonne.

Słowa kluczowe: AHP, Rembrandt, biomonitoring, biologiczny system wczesnego ostrzegania