The assessment of drinking water quality using zero unitarization method

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Abstract: The work is an attempt to assess piped water quality in four counties located in east central Poland. Piped water was analysed for three successive years in each county. Water samples were tested for the following physical and chemical parameters: turbidity, colour, conductivity, taste, odour, pH, nitrates (III), nitrates (V), iron and manganese. They were compared with the current standard values. Preliminary data analysis included an analysis of maximum and minimum values of physical and chemical parameters, and it revealed that turbidity, colour, iron and manganese contents exceeded the permissible standards in all the counties. Percentages of parameters exceedances and mean values of the exceedances were used to rank the counties in terms of water quality. The ranking was obtained by means of multidimensional comparative analysis. It was demonstrated that best quality water was supplied by Węgrów County water supply system which was followed by Mińsk Mazowiecki County. The third rank was assigned to Łosice County and the poorest quality water was found to be supplied by Siedlce County water supply system.

Introduction

Drinking water for communal purposes is provided by water supply and sewerage companies which abstract, treat and supply water to consumers. They are required by law to provide a continuous supply of good quality water. The companies are obliged to conduct checks of water quality on a regular basis. To ensure that all the standards are met, it is necessary to check water physical and chemical, biological, and organoleptic parameters when water leaves the abstraction place, is transported through the distribution system and is released in taps (Mikołajski et al. 1997). The quality of piped water is influenced by such factors as: source of water abstraction, method of water abstraction and treatment, the sanitary condition of water intake and water storage tanks, pipes distributing water, water connections and internal household water systems. Piped water for consumption should not contain harmful chemical components and pathogenic microbes. It is increasingly difficult to achieve this target as abstracted water which enters water systems is more and more polluted and methods of treatment are not efficient enough to ensure that water is totally safe (Pawlaczyk-Szpilowa 1992, Włodyka-Bergier et al. 2011).

When standard values are exceeded for only short periods of time, the water does not necessarily have to be unsuitable for consumption. However, the length of the period and the extent of exceedances which may influence human health depend on the substance or parameter they refer to. Nevertheless, measures should always be taken when standard values have been exceeded (Zięba 1995). Based on reports of an assessment of water quality prepared by laboratories, the respective sanitary inspector may formulate the following conclusions: water is suitable for consumption, water is suitable for consumption under conditions of departure granted by the Chief Sanitary Inspectorate, conditional suitability of water for consumption and water unsuitable for consumption. The control procedures that are carried out have to comply with a number of laws (Guidelines 2004, The Order 2010). Water quality checks have gradually developed into a system of water quality management. Drinking water quality is standardized and checked all over the world and, as a result, an assessment of its suitability for consumption has already been attempted in many works (Bergel et al. 2009, Bergel et al. 2011, Eckner 1988, Rak 2009, Roman 2003, Rosińska et al. 2011, The Provision 2011, Włodyka-Bergier et al. 2011, Vircavs 2009, Zięba 1995).

To assess water quality, it is necessary to determine values of all the physical, chemical and biological parameters (Eckner 1988, Gromiec 2004). As water quality is described by many parameters, it has to be analysed by means of multidimensional methods, e.g. multidimensional comparative analysis which enables simultaneous comparisons of objects in terms of many traits. Many input variables are used to produce the so-called synthetic variable. The variable is the basis for

an identification of relations (patterns) between objects in a set which are then ranked.

Thus, the objective of this work was to assess the quality of piped water supplied in four counties of east central Mazovia by means of multidimensional comparative analysis. Based on values of synthetic variables, the counties were ranked for the quality of piped water distributed through water supply systems.

Materials and methods

Database comprised results of an assessment of piped drinking water quality in the following four counties in east central Mazovia: Łosice, Mińsk Mazowiecki, Węgrów and Siedlce. Water in each county was supplied by respectively, 15, 21, 18 and 10 systems. The results were obtained from the Local Sanitary-Epidemiological Centres. Analysis for each county spanned three successive years. Samples for analysis were taken four times per calendar year following the Polish standards. The following physical and chemical parameters were determined in the samples: turbidity (nephelometric method), colour (colorimetric method), conductivity (conductivity measurement method), odour and taste (organoleptic method), pH (potentiometric method), nitrates (III), nitrates (V) and iron (spectrophotometric method) and manganese (atomic absorption spectroscopy). The results obtained were compared with the standards detailed in the order of the Minister of Health of 29th of March 2007 on the quality of water for human consumption (OJL No 61, item 417).

Preliminary analysis included examination of maximum and minimum values of physical and chemical parameters of water quality in the four counties over the study period, and comparison of these values with the current standards. The analysis that followed included only the parameters that exceeded the standard. Percentages of exceedances ($\%_p$) and mean values of parameter exceedances ($\overline{x}_{wp}$) were calculated for each county and parameter exceeded. Percentages of exceedances were computed as a percentage ratio of number of exceedances to number of supply systems. Mean values of parameter exceedances were calculated as average values of parameter deviation from the standard. Percentages of parameter exceedances and mean values of the exceedances were used to rank counties in terms of water quality. The ranking was determined using the multivariate comparative analysis which makes it possible to simultaneously organise and group objects in terms of many traits. The multivariate comparative analysis, which is based on normalised unitless values of traits, makes it possible to produce one (instead of many) synthetic variable reflecting a complex phenomenon. The key issue in this analysis is to determine which traits should have as high values as possible (stimulants), which ought to have the lowest values possible (destimulants) and which should have precisely defined – optimal – values (nominants). It follows from the fact that formulas of normalisation are different for these groups of traits.

The counties were compared in terms of the following traits:
1. percentage of exceedances of turbidity units,
2. percentage of exceedances of colour units,
3. percentage of exceedances of nitrate (V) content,
4. percentage of exceedances of nitrate (III) content,
5. percentage of exceedances of Fe content,
6. percentage of exceedances of Mn content,
7. mean value of exceedances of turbidity units,
8. mean value of exceedances of colour units,
9. mean value of exceedances of nitrate (V) content,
10. mean value of exceedances of nitrate (III) content,
11. mean value of exceedances of Fe content,
12. mean value of exceedances of Mn content.

As all the aforementioned traits were destimulants in character, normalisation was conducted following the formula (Kowalski 2009):

$$z_{ij} = \frac{1}{b_i - a_i}(b_i - x_{ij})$$

in which:
z_{ij} – normalised value of the i-th parameter for the j-th county, $i = 1, ..., 12, j = 1, ..., 4$;
x_{ij} – value of the i-th parameter for the j-th county, $i = 1, ..., 12$, $j = 1, ..., 4$;
a_i – minimum value of the i-th parameter;
b_i – maximum value of the i-th parameter.

Normalised values of traits reflecting water quality were aggregated, that is they were summed up and then averaged (the sum was divided by 12 which was the number of traits) to obtain one value of the so-called synthetic variable q_i which was the basis of ranking the counties in terms of the quality of water supplied. Based on the synthetic variable's arithmetic mean ($\overline{q}$) and standard deviation (s_q) the following four groups were identified:

– group 1 $q_j \geq \overline{q} + S(q)$,

– group 2 $\overline{q} \leq q_j < \overline{q} + S(q)$,

– group 3 $\overline{q} - S(q) \leq q_j < \overline{q}$,

– group 4 $q_j < \overline{q} - S(q)$

Results and discussion

Minimum and maximum values of parameters of drinking water distributed by each county's water supply system are presented in Table 1. The odour and taste of the piped water were appropriate in all the systems. Its pH ranged from 6.5 to 9.5 and was within the standard limits. Similarly, conductivity values, ranging from 77 to 658 $\mu S/cm^3$, fell within the permissible limits.

Maximum values of the studied parameters indicated that turbidity, colour, iron content and manganese content exceeded the permissible values in all the four counties. What is more, permissible nitrate (III) contents were exceeded in Mińsk Mazowiecki County and Siedlce County, whereas permissible nitrate (V) contents were exceeded in the latter county only. The analysis of maximum values of individual parameters revealed that the values of the following parameters were the highest in Siedlce County: colour and nitrates (V), in Mińsk Mazowiecki County: turbidity, nitrates (III) and iron content, and in Węgrów County: turbidity and manganese content. Over-standard values of water quality parameters have been reported by Bergel et al. (2009) and Piekutin (2012). According to these authors, water quality in

small water supply systems, rural in particular, may sometimes not meet the standards due to treatment technologies applied or improper operation of the mains system. In turn, water quality in municipal supply systems (as demonstrated by the results of NIK (the Supreme Chamber of Control, audit in 2000) did not meet the drinking water standards in two-thirds of the towns checked. Water abstracted from surface sources contained too much nitrite nitrogen, phosphorus and phosphates. Infiltration waters supplied to households had excessive amounts of manganese, whereas underground waters did not meet standards in terms of turbidity, iron, manganese and ammonia contents (NIK 2002).

The analysis of data presented in Table 2 revealed that the lowest percentages of water turbidity and iron content exceedances were recorded in Węgrów County. They were accompanied by low mean values of exceedances for these parameters amounting to 3.18 mg Pt/dm^3 and 0.45 mg/l, respectively. Nitrate contents (nitrates (V) and (III)) in the water supply systems remained within the permissible limits (Tab. 2).

Values of synthetic variable demonstrated that the best quality water was supplied in Węgrów County. The value of synthetic variable describing the multi-trait water quality ranked the county as number 1 (Tab. 3). Mińsk Mazowiecki

Table 1. The minimum and maximum values of physical and chemical water quality parameters in the studied counties

Parameter	Unit	Permissible standard	County							
			Mińsk Mazowiecki		Węgrów		Siedlce		Łosice	
			Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Turbidity	NTU	1	1.10	11.8	0.1	11.8	0.2	8.1	0.1	11.1
Colour	mg Pt/ dm^3	15	5	20.0	5.00	25.0	5.00	50.0	5.0	25.0
Conductivity	$\mu S/cm^3$	2500	77	636	260	629	178	610	274	658
Odour	accep.	accep.	x	x	x	x	x	x	x	x
Taste	accep.	accep.	x	x	x	x	x	x	x	x
pH	–	6.5–9.5	6.5	9.5±0.5	6.5	8	7.40	7.9	6.7	7.8
Nitrates (III)	mg/dm^3	0.5	0.003	0.947	0.04	0.11	0.40	0.58	0.03	0.078
Nitrates (V)	mg/dm^3	50	0.003	44.20	2.20	18.0	0.00	81.0	1.8	40.1
Iron	mg/dm^3	0.2	0.005	3.677	0.05	1.04	0.001	2.67	0.05	0.58
Manganese	mg/dm^3	0.05	0.005	0.209	0.005	0.413	0.007	0.225	0.015	0.061

Table 2. The percentage of exceedances and average values of exceedances of physical and chemical parameters of water quality in the studied counties

Parameter	County							
	Mińsk Mazowiecki		Węgrów		Siedlce		Łosice	
	%p	$\overline{x}_{wp}$	%p	$\overline{x}_{wp}$	%p	$\overline{x}_{wp}$	%p	$\overline{x}_{wp}$
Turbidity	27.1	4.15	13.4	3.18	53.3	2.91	50.0	30.3
Colour	3.4	13.3	5.60	10.0	10.0	25.0	11.9	6.5
Nitrates (III)	0.30	0.15	0.00	0.00	0.2	0.08	0.00	0.00
Nitrates (V)	0.00	0.00	0.00	0.00	20.0	27.5	0.00	0.00
Fe content	22.4	0.65	18.9	0.45	37.0	0.76	71.3	0.29
Mn content	31.9	0.08	42.8	0.10	20.0	0.13	35.7	0.12

$\%_p$ – percentage of exceedances
$\overline{x}_{wp}$ – average value of exceedances

Table 3. Synthetic variable values, ranking and groups formed

County	Value of synthetic variable q_i	Ranking of counties	Grup
Mińsk Mazowiecki	0.657	Węgrów	Group 1 $q_i \geq 0.798$
Węgrów	0.820	Mińsk Mazowiecki	Group 2 $0.583 \leq q_i < 0.798$
Siedlce	0.307	Łosice	Group 2 $0.368 \leq q_i < 0.583$
Łosice	0.550	Siedlce	Group 4 $q_i < 0.368$

County, which had the highest percentage (0.3%) of water supply systems where nitrate (III) contents were exceeded by 0.149 mg/l on average, was ranked second. Moreover, this county had the lowest percentage of mains systems where colour units were exceeded. Although, the percentage exceedance for manganese was almost 32%, the mean value of exceedances was the lowest of the four counties studied (0.08 mg/l).

The quality of piped water in Łosice County was slightly poorer and, as a result, the county was ranked third based on the value of synthetic variable describing water quality in terms of 12 characteristics. The county had the greatest percentage of exceedances for colour (11.9%) and iron content (71.3%) but mean values of the exceedances for these parameters were the lowest and amounted to, respectively: 6.5 mg Pt/dm^3 and 0.293 mg/l. Nitrate contents for this county felt within the permissible limits set by the standards.

Siedlce County was ranked fourth as it had the greatest percentages of turbidity and nitrogen (V) exceedances (53.3% and 20%, respectively). Moreover, water in the county's mains systems had higher-than-standard nitrate (III) contents, the greatest number of iron content exceedances (iron content was exceeded in 37% cases), the highest value of exceedances for colour and manganese (the latter had the lowest percentage of exceedances). Similar results have been reported by Piekutin (2012) who analysed water quality supplied through rural mains systems. Water with excessive turbidity had over--standard iron and manganese contents.

Despite actions undertaken to improve drinking water quality, there are cases when standards are not met, as has been demonstrated in the present work. According to Kowalski (2009), inappropriate piped water quality may be due to insufficient number of measures improving the quality of water in the mains system.

Conclusions

1. All the supply systems distributed water characterised by appropriate pH, taste, odour and conductivity.
2. Maximum values of parameters determined indicate that turbidity, colour, iron content and manganese content exceeded the permissible standards in all the counties where studies were carried out. Nitrate contents were exceeded in two counties only, i.e., Mińsk Mazowiecki County and Siedlce County (nitrates (III) and (V)).
3. Multidimensional comparative analysis demonstrated that the highest-quality water was supplied in Węgrów County where there were found the lowest percentages of exceedances for water turbidity and iron content, and which also had the lowest values of deviation from the standard.
4. Siedlce County was ranked in the last place in terms of the quality of piped water supplied to households as it had the greatest percentages of exceedances for turbidity (53.3%) and nitrates (V) (20%) and above-standard nitrate (III) and (V) contents.
5. Zero unitarization method was found to be suitable for an assessment of drinking water quality. A number of parameters have been used to produce a synthetic variable which makes it possible to rank objects based on the quality of piped water.

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Zastosowanie wielowymiarowej analizy porównawczej do oceny jakości wody pitnej

Streszczenie: W pracy dokonano oceny jakości wody wodociągowej w czterech powiatach środkowo-wschodniego Mazowsza. Ocenie była poddawana woda z sieci wodociągowej. Dla każdego powiatu analizę przeprowadzono w okresie trzech kolejnych lat. W pobranych próbkach badano następujące, parametry fizyczne i chemiczne: mętność, barwa, przewodnictwo elektryczne, zapach, smak, odczyn, azotyny, azotany, żelazo, mangan. Porównano je z obowiązującymi normami. Wstępna analiza danych polegała na przeanalizowaniu maksymalnych i minimalnych wartości wskaźników fizykochemicznych. Na tej podstawie stwierdzono, że mętność, barwa, zawartość żelaza oraz manganu przekroczyły dopuszczalną normę we wszystkich analizowanych powiatach. W dalszej analizie uwzględniono tylko te wskaźniki, które uległy przekroczeniu. Odsetki przekroczeń wskaźników oraz średnie wartości ich przekroczeń stanowiły podstawę budowy rankingu powiatów pod względem jakości wody. Ranking ten ustalono z wykorzystaniem wielowymiarowej analizy porównawczej. Wykazano, że najlepsza woda dostarczana jest przez wodociągi powiatu węgrowskiego. Na drugim miejscu w rankingu uplasował się powiat miński, na trzecim łosicki, a na czwartym siedlecki.