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ECONOMIC AND ENVIRONMENTAL ASPECTS IN MODELLING MONTHLY WATER DEMAND IN BIAŁYSTOK – A CASE STUDY

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CZYNNIKI EKONOMICZNO-ŚRODOWISKOWE W MODELOWANIU MIESIĘCZNEGO ZAPOTRZEBOWANIA NA WODĘ NA PRZYKŁADZIE BIAŁEGOSTOKU

STRESZCZENIE: W pracy zaprezentowano wybrane czynniki mające potencjalny wpływ na miesięczne zapotrzebowanie na wodę w białostockim systemie wodociągowym. Początkowo rozważono czynnik ekonomiczny tj. cenę za wodę i odprowadzanie ścieków. Następnie przeanalizowano zależność pomiędzy miesięcznym zużyciem wody a czterema wybranymi aspektami środowiskowymi. Ostatecznie, oszacowano pięć liniowych modeli ekonometrycznych. W pierwszym modelu, opisującym zmienność zużycia wody od września do kwietnia, jako zmienną objaśniającą przyjęto tylko cenę za wodę. Pozostałe modele dotyczą miesięcy od maja do sierpnia i uwzględniają, oprócz ceny za wodę, również zmienność parametrów meteorologicznych (opadów oraz temperatury powietrza). Opracowane modele charakteryzuje bardzo dobre dopasowanie danych teoretycznych do danych rzeczywistych.

SŁOWA KLUCZOWE: miesięczne zapotrzebowanie na wodę, miejski system wodociągowy, regresja liniowa

Introduction

The basic element in the planning, design and operation of water supply systems is the analysis of water use aimed at the identification of relationships and trends characteristic for the analysis process[1]. There are many methods for the analysis of variability and forecasting water demand, including time series analyses, indexing methods and correlation methods[2]. The latter method allows for the determination of the relationship between the volume of water supplied by the water system in the past, and factors determining this volume. Long-term and medium-term water use are often characterised and forecasted using econometric models based on linear regression[3].

Analysis of the demand for water in urban areas is particularly important because of the declining trend in the volume of used water, which has persisted for many years[4]. This decline in water use is indirectly caused by technical, social and economic changes[5], determined by such factors as reduced number of system failures[6], gradual modernization of water supply systems and their effective monitoring by means of integrated IT systems supporting the management of waterworks companies[7]. The decreasing water use is also a consequence of raised awareness of the value of water, its price, and the increasing affluence of citizens, which, for example, allows them to buy water saving appliances and good quality sanitary fittings. In addition, the annual, monthly and daily water demand is also affected by environmental factors such as changes in meteorological parameters, particularly rainfall and average air temperature[8].

1 Z. Siwoń, W. Cieżak, J. Cieżak, *Analiza i prognozowanie szeregów czasowych krótkotrwałego poboru wody,* „INSTAL" 2006 No. 2, pp. 44–49.

2 H. Hotloś, *Analiza wpływu czynników meteorologicznych na zmienność poboru wody w miejskim systemie wodociągowym*, „Ochrona Środowiska" 2013 No. 2, pp. 57–61.

3 J. Adamowski, Hiu Fung Chan, S.O. Prasher, B. Ozga-Zielinski, A. Silisarieva, *Comparison of multiple linear and nonlinear regression, autoregressive integrated moving average, artificial neural network and wavelet artificial neural network for urban water demand forecasting in Montreal Canada*, "Water Resources Research" 2012 No. 48, pp. 1–14.

4 L. Kłos, *Dostępność do wody jako jeden z obszarów realizacji Milenijnych Celów Rozwoju*, „Ekonomia i Środowisko" 2014 No. 3(50), pp. 167–175.

5 A. Thier, *Aksjologiczne, ekonomiczne i społeczne problemy gospodarki wodnej*, „Ekonomia i Środowisko" 2015 No. 3(54), pp. 10–24.

6 I. Zimoch, E. Szymura, *Klasyfikacja stref systemu dystrybucji wody według wskaźników strat wody i awaryjności sieci*, „INSTAL" 2013 No. 7/8, pp. 64–68.

7 A. Trębicka, *Modelowanie i prognozowanie systemów związanych z dystrybucją wody*, „Ekonomia i Środowisko" 2013 No. 4(47), pp. 245–254.

8 A. Yasar, M. Bilgili, E. Simsek, *Water Demand Forecasting Based on Stepwise Multiple Nonlinear Regression Analysis,* "Arabian Journal of Science and Engineering" 2012

The aim of this study was to analyze the impact of meteorological factors (air temperature, air humidity, monthly rainfall and cloud cover) on the monthly water demand in the water supply system for the city of Białystok. Linear econometric models of monthly water use were created taking into account weather conditions, but also an economic factor – the price of water and sewage treatment in the area of Białystok. The purpose of the designed mathematical models was to identify future trends in water use and the effect of external factors shaping demand for water.

Monthly water use in Białystok

In this analysis, the monthly water demand was calculated as the arithmetic mean of daily measurements in a given month, multiplied by 30, i.e. the average number of days in each month. The analysis at this level covered years 2001–2013, including a total of 156 elements of the time series (months). The necessary baseline data were provided by the Białystok waterworks company (Wodociągi Białostockie sp. z o.o.).

The analysis of time series for monthly demand for water showed a clear decreasing trend. The figure illustrating monthly water use in 2001–2013 clearly shows descending broken lines correlated with time. For the purpose of clarity the figure shows only data for odd years. The mean monthly demand for water in 2001–2013 was 1.34 million m^3. The highest mean monthly value of the analysed variable was 1.54 million m^3 (in 2001) and the lowest was 1.19 million m^3 (in 2013). A slightly increasing trend between January and April was found, as well as clearly increased water use from May to August, followed by a decrease in water use until the end of the year (Figure 1).

Previous analyses of monthly demand for water in Białystok identified three specific seasons during the year[9]:

- Season one: from January to April;
- Season two: from May to August;
- Season three: from September to December.

A decomposition of the time series was carried out to calculate the percentage of individual systematic components of the time series. The greatest variability in water demand was found for season 2, between May and

No. 37, pp. 2333–2341; P.K. Tuz, J. Gwoździej-Mazur, K. Barbarczyk, *Wybrane aspekty prognozowania zużycia wody w budownictwie wielorodzinnym*, „INSTAL" 2003 No. 5, pp. 40–43.

9 M. Kolendo, *Zmienność zapotrzebowania na wodę w systemie wodociągowym Białegostoku* in: A. Dzięgielewski, D. Szychowski, J. Wernik (eds), *Wybrane problemy techniki*, Płock 2015, pp. 228–237.

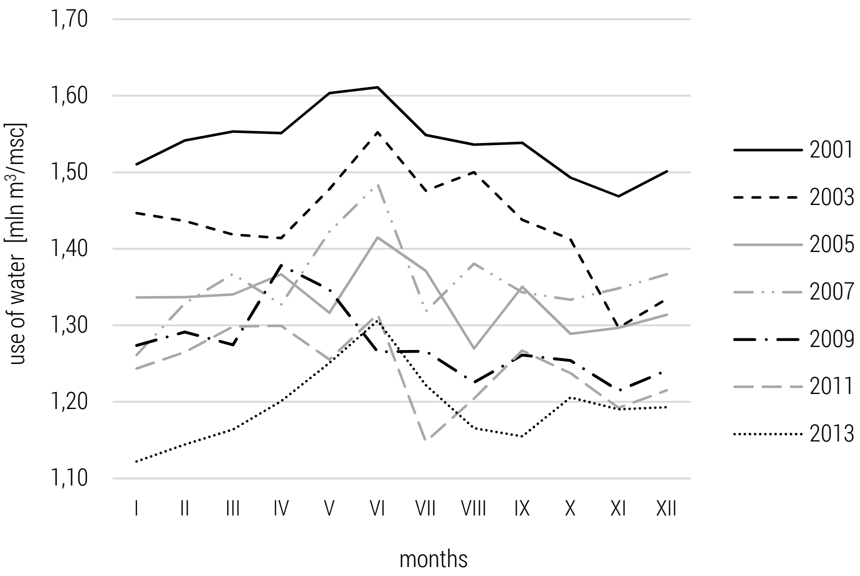

Figure 1. Total monthly demand for water in 2001–2013

Source: author's own analysis based on data from Wodociągi Białostockie.

August[10]. Throughout the year, water use was affected by the declining trend, persisting for many years, in water use, while from May to August additional and greater seasonal and random fluctuations than in other months were recorded (Figure 2).

Effects of individual factors on the use of water

Detailed analysis of monthly water use included one economic factor (price for water and sewage treatment [PLN/m^3]) and four environmental factors (air temperature [C], air humidity [%], rainfall [mm], and cloud cover [oktas]). Research by the author on annual water use indicates that long-term directional changes in water use are determined largely by the growing prices for water and sewage treatment. In 2001–2013 an almost two-fold increase in these prices was observed (from 3.13 PLN/m^3 in January 2001 to 6.42 PLN/m^3 in December 2013). The correlation coefficient for the mean annual prices for water and sewage treatment and the annual demand for water was-0.95.

10 Ibidem.

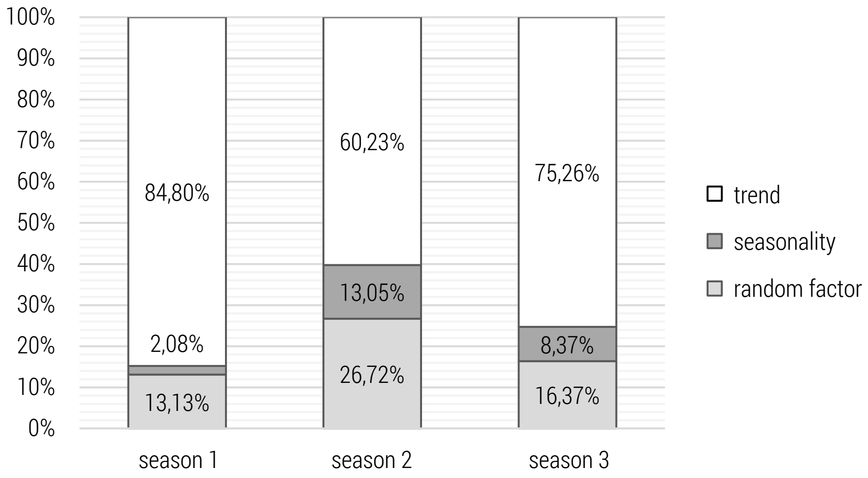

Figure 2. The share of systematic components in the three identified seasons

Source: based on: M. Kolendo, *Zmienność zapotrzebowania na wodę w systemie wodociągowym Białegostoku* in: A. Dzięgielewski, D. Szychowski, J. Wernik (eds), *Wybrane problemy techniki*, Płock 2015, pp. 228–237.

In addition, the independent variables in the model were chosen with a focus on the greatest variability of water use between May and August. Therefore, a detailed analysis was carried out for the fluctuations in the volume of used water and changes in meteorological conditions in these months. To identify seasonal fluctuations the monthly series of water use were transformed into a stationary time series to eliminate directional changes. Due to the fact that the trend is one of the factors interfering with the stationarity, the non-stationarity of the time series was identified by a simple visual analysis. The first increments of the series were calculated in order to achieve the stationarity. The created order 1 integrated time series was created ($Y_tI(1)$), and shows only seasonal and random fluctuations (the effect of the trend was eliminated).

In order to identify the relationship between increased seasonal and random fluctuations from May to August the values of an integrated series of monthly demand for water [million m$^{3]}$ were compared to meteorological parameters, i.e. average monthly air temperature [C], rainfall [mm], air humidity [%] and cloud cover [oktas]. Meteorological data for the station in Białystok (WMO index – 12295) were acquired from the OGIMET web service[11].

[11] Statistics from www.ogimet.com [10/07/2015].

Calculated values of the correlation between meteorological parameters and the average monthly water demand in 2001–2013 are presented in Table 1. The calculated correlation coefficients were generally lower in winter, early spring and autumn months than in late autumn and the summer months. This was taken into account in the further analysis focused on the effects of individual meteorological conditions on water use in season 2.

Season 2 was characterised by the strongest correlation between monthly demand for water and weather conditions, which confirmed earlier findings. The increased cloud cover, rainfall and air humidity caused a decrease in water demand. The strongest correlation between these parameters and use of water was recorded in June. The analysis of the relationship between monthly demand for water and average monthly air temperature revealed the highest value of Pearson's correlation coefficient in May (r = 0.84), (Table 1).

Table 1. Correlation coefficients for meteorological parameters and an integrated time series (Yt I(1)) for average monthly water use in 2001–2013

Months/parameters		Temperature [°C]	Air humidity [%]	Rainfall [mm]	Cloud cover [oktas]
Season 1	January	-0.33	-0.12	-0.55	-0,13
	February	-0,55	0,27	-0,43	0,21
	March	-0,04	-0,39	-0,53	-0,21
	April	0,23	-0,25	-0,34	-0,47
Season 2	May	0,84	-0,34	-0,61	-0,71
	June	0,24	-0,76	-0,61	-0,70
	July	0,66	-0,60	-0,54	-0,73
	August	0,47	-0,63	-0,84	-0,60
Season 3	September	0,58	0,31	-0,15	-0,17
	October	0,11	0,48	-0,40	0,04
	November	-0,37	-0,16	0,00	0,06
	December	-0,45	-0,54	-0,06	0,23

Source: author's own analysis based on data from Wodociągi Białostockie.

The significant effect of weather conditions on the use of water in season 2 was characterised using the example of May (Figures 3 and 4). In May the correlation between water demand and air temperature was the strongest. The increase in average monthly air temperature in May caused a noticeable increase in water demand. The largest increase in water use was found in May 2002. The average monthly air temperature in May 2002 was also the highest (about 16°C) considering all the 13 analysed years. A clear correlation between air temperature and use of water was found, as demonstrated in the figure below (Figure 3).

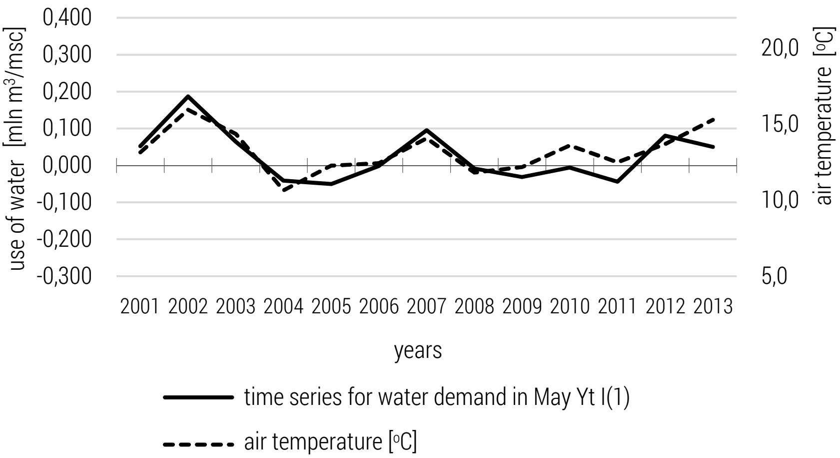

Figure 3. Time series for water demand Y_tI(1) and the average monthly air temperature in May in years 2001–2013.

Source: author's own analysis based on data from Wodociągi Białostockie and www.ogiment.com.

In May the use of water was also significantly determined by rainfall. The correlation coefficient for these two variables was –0.61. In the study period the minimum rainfall was recorded in 2002 (Figure 4). In the same year the greatest increase in water demand (by 0.187 million m^3) was also recorded compared to 2001. Of note is that 2002 was characterized by extremely low levels of rainfall and high air temperature, which resulted in a significant increase in water demand. Figure 4 shows decreased water use at the time of higher rainfall.

The above analysis demonstrates that weather conditions had a significant impact on the use of water between May and August (season 2), and at that time the demand for water was the highest and also characterised by the strongest fluctuations. Therefore, the inclusion of meteorological variables is particularly recommended when designing a monthly model of water demand for season 2.

Model of monthly water demand

The above analysis demonstrates that throughout the year water demand is affected by the declining trend, persisting for many years, in the use of water, largely explained by the growing price for water, while from May to August additional and greater seasonal and random fluctuations than in other months are recorded (Figure 4).

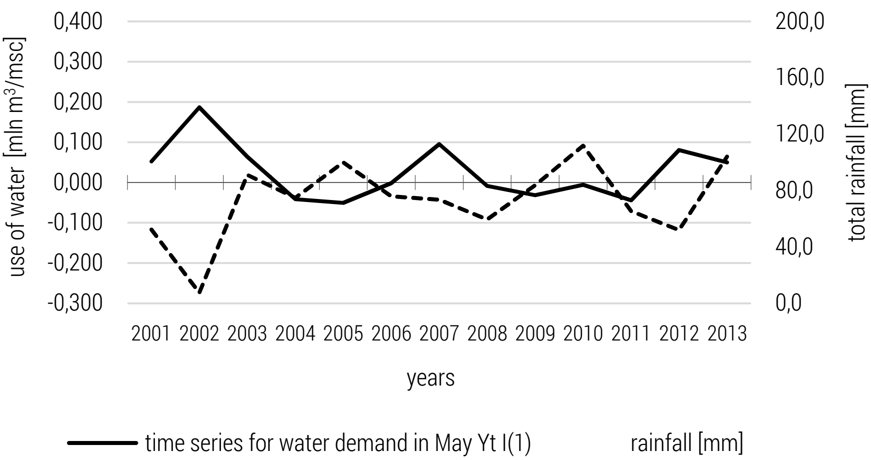

Figure 4. Time series for water demand $Y_tI(1)$ and the total rainfall in May in years 2001–2013.

Source: author's own analysis based on data from Wodociągi Białostockie and www.ogimet.com

Bearing in mind the previous considerations regarding the identification of three distinctive seasons, an attempt was made to describe these periods using separate models. It was concluded, taking into account the percentage of individual systematic components in the distinguished seasons, that due to the small share of the seasonal and random fluctuations in seasons 1 and 3 it would be sufficient to describe the months from January to April and from September to December using a single linear model including only the price for water and sewage treatment as an independent variable. The inclusion of meteorological factors is justified only for the second season (from May to August). Using the Classical Least Squares (CLS) method the following linear model for seasons 1 and 3 was estimated:

$$\mathbf{Y = 1{,}762 - 0{,}1822\, X_1}$$
$$(0{,}0195)\ (0{,}00786)$$

where:
X_1 – price for water and sewage treatment [PLN/m^3].

The above equation shows that from September to April the price for water increased by 1 PLN/m^3 and results in a monthly decrease in water demand by 0.1822 million m^3. This model explained 85.04% of the variability in water demand in the indicated months of the analysed period. All structural parameters were statistically significant. Estimation errors were small: 1.1% of a structural parameter for the constant term, and 4.3% for a parameter with variable X_1.

Separate models were also considered for seasons 1 and 3, which had similar compatibility between simulated and real data. The coefficient of determination for season 1 ($Y = 1.786 - 0.1893\ X_1$) was R^2=85.45%, and for season 3 ($Y = 1.729 - 0.1720\ X_1$) was R^2=83.04%. Linear trend models were also considered in the study, and they provided comparable results because of the relatively steady growth of the price for water and sewage treatment over time.

In analyses related to season 2 different econometric models and a diverse range of external factors were considered. The best compatibility of simulated and real data and the lowest errors of the estimate for parameters were obtained using a linear approximation model, CLS method and a different model for each month from May to August. Parameters and errors of the estimate obtained for individual months are presented in Table 2.

Considering the above results, linear models for individual months were expressed by the following equations:

MAY: $\mathbf{Y = 1{,}4796 - 0{,}1818\, X_1 + 0{,}0344\, X_2 - 0{,}0017\, X_3}$
JUNE: $\mathbf{Y = 1{,}9134 - 0{,}1763\, X1 - 0{,}0008\, X_3}$
JULY: $\mathbf{Y = 1{,}0973 - 0{,}1687\, X_1 + 0{,}0383\, X_2 - 0{,}0006\, X_3}$
AUGUST: $\mathbf{Y = 1{,}0275 - 0{,}1929\, X_1 + 0{,}0486\, X_2 - 0{,}0009\, X_3}$

Table 2. Structural parameters of econometric models for individual months

Variable	May		June		July		August	
	b	bł. z b	b	bł. z b	b	bł. z b	b	bł. z b
Constant term	1,4796	0,1189	1,9134	0,0646	1,0973	0,1199	1,0275	0,2607
Price X_1	-0,1818	0,0253	-0,1763	0,0007	-0,1687	0,0170	-0,1929	0,0253
Temperature X_2	0,0344	0,0082	-	-	0,0383	0,0055	0,0486	0,1295
Rainfall X_3	-0,0017	0,0005	-0,0008	0,0285	-0,0006	0,0002	-0,0009	0,0003
R^2	0,9280		0,8660		0,9703		0,9374	

Where: b – value of a structural parameter; bł. z b – standard error of the estimate for a structural parameter

All structural parameters of linear models were statistically significant at the adopted level of confidence $\alpha = 0.10$. In the case of June, due to the large error of the estimate for the parameter (68.13% of the structural parameter) with variable X_2 describing air temperature, the model included only fluctuations in the prices for water and total monthly rainfall. The validity of the removal of variable X_2 from the model was also justified by a small (about 0.025) difference in the coefficient of determination for both analyzed econometric models.

The analysis of the values of the obtained structural parameters (Table 2) showed a correlation between the increase in prices for water and a decrease in water use in the range from 0.1687 to 0.1929 million m^3/month. The increase in air temperature had a positive effect on the increase in water demand, and this trend was most pronounced in August (b=0.0486). The impact of fluctuations in total rainfall was strongest in May. The structural parameter at the level of 0.0017 indicates that an increase in rainfall by 1 mm results in a decrease in water use by 0.0017 million m^3/month. This index is almost two-fold higher for May compared to other months. The factual verification of the calculated parameters of econometric models indicated that they are consistent with general knowledge. The correctness of the obtained multiple regression equations is also supported by the compliance between parameter signs and Pearson's correlation coefficients, implying the coincidence of models.

The analysis of the obtained values of the coefficient of determination (Table 2) revealed that all the estimated models are characterised by a very good compatibility between simulated and empirical data. The linear model describing changes in water demand in July, taking into account three independent variables (prices for water, air temperature, rainfall), explained 97.03% of the variability in water demand in this month. The R^2 coefficient for May and August was about 93%, and the lowest value of this parameter was found in June (R^2=0.8660%). Compatibility between simulated and empirical data is presented in Figure 5.

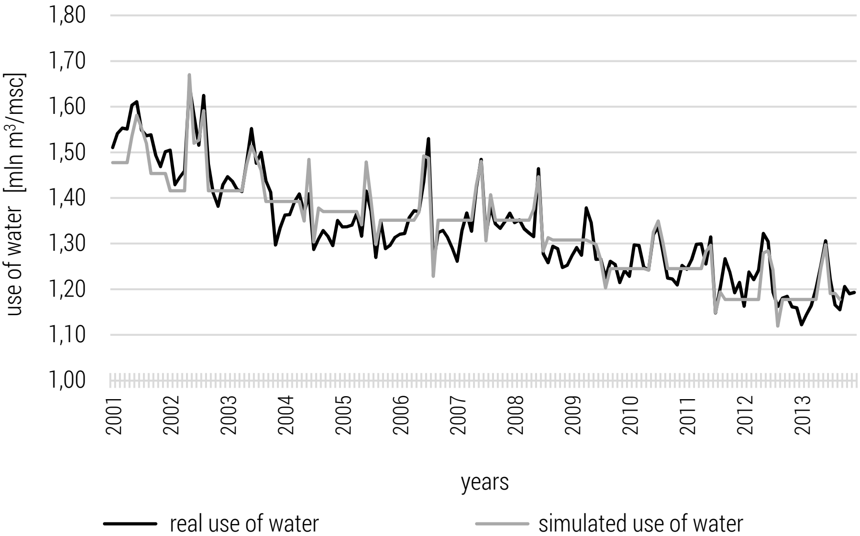

Figure 5. Real vs simulated data on water demand.

The study also considered a seasonal model of monthly water demand including all months between 2001 and 2013 (156 observations). Estimation was carried out for a model with constant seasonal dummy variables (Z_1, Z_2, Z_3) and three external variables: the price for water (X_1), air temperature (X_2) and rainfall (X_3). The obtained model explained 84.77% of the variation of the dependent variable. All the estimated structural parameters of the modified model were statistically significant, but a relatively high error of the estimate was found for seasonal variables. A similar analysis was also carried out for the seasonal linear model which did not include external variables X_1, X_2 and X_3. The model estimated with the generalized least squares (GLS) technique explained 79.88% of the variation, and therefore the elimination of three dependent variables reduced the coefficient of determination by about 0.05.

Conclusions

Considering all the above findings on the modelling of monthly water demand in Białystok, a combination of five linear functions, i.e. a linear model for seasons 1 and 3 and four linear functions for each month of the season 2 (May – August) was assumed as the best mathematical description of the analysed process. The introduction of meteorological variables, i.e. total monthly rainfall and air temperature is justified only in the period from May to August, while in the remaining months a declining trend clearly prevails and is largely determined by the increasing price for water and sewage treatment.

The obtained linear models are characterised by very good compatibility of simulated and real data. Coefficients of determination for all obtained linear models are higher than 85%. The lowest value of R^2 (85.45%) was found for the model describing water use in autumn and winter months. This may be attributed to the fact that only the economic factor (price for water) was considered. About 15% of variability of the analysed process unexplained by the model can be attributed to many different factors, including the increase in the metering of water use and reduced failure rate of the water supply network.

The analysis of variability of water use in water supply systems showed relationships and trends in the analysed process and allowed for the development of a mathematical model describing monthly demand for water. The developed models can be applied for the forecasting of water use in the analysed area, which is an important issue in view of the optimised control of the general process of water supply.

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