https://doi.org/10.5194/hess-2024-41
Preprint. Discussion started: 14 March 2024

Hydrology and Earth System Sciences
Discussions

Support system for heat pump planning in response to drought conditions

Justyna Kubicz[1], Maciej Karczewski[2]

[1] Wroclaw University of Environmental and Life Sciences, Institute of Environmental Engineering, 24 Grunwaldzki Sq., 50-363 Wroclaw, Poland
[2] Wroclaw University of Environmental and Life Sciences, Department of Applied Mathematics, 53 Grunwaldzki Sq., 50-363 Wroclaw, Poland

Correspondence to: Justyna Kubicz (justyna.kubicz@upwr.edu.pl)

Abstract. Access to extensive data enables advanced research on the impacts of climate change, specifically drought, on groundwater resources and their consequential effects on water quality. While scientific studies offer insights into predicting groundwater shortages at a high level, the data often remain inaccessible and incomprehensible to potential users. To bridge this gap, this study proposes a relatively straightforward method for assessing the risk of groundwater availability for heat pump usage. The method involves creating informative color-coded charts illustrating periods of potential excessive groundwater level decline near utilized wells. Additionally, it provides the ability to monitor changes in the risk of groundwater level reduction within a predefined observational period.

During droughts, groundwater levels can significantly drop, impacting groundwater availability and potentially reducing heat pump efficiency. This, in turn, may lead to system overheating, decreasing effectiveness, and causing damage. Exceeding critical groundwater levels may result in well infrastructure damage, affecting water quality and energy extraction efficiency. Excessive well exploitation often leads to chemical and mechanical clogging, further influencing well performance.

In contrast to commonly used hydrogeological drought indicators, this method focuses on a probabilistic model, simplifying calculations as it only requires historical groundwater level data. By applying statistical tests and distribution functions, the study evaluates the risk of extreme groundwater level reduction. The proposed method categorizes risk into very high, high, moderate, and low levels, providing a practical tool for users and groundwater management.

The study area, located in the northwest Eurasian continent, encompasses diverse geological and hydrogeological settings. Utilizing data from 27 groundwater observation points, spanning from 1980 to 2020, the research identifies periods and regions at risk of groundwater depletion. The findings highlight specific points vulnerable to high or very high risks, emphasizing the importance of groundwater management strategies.

By analysing monthly, quarterly, and seasonal risk variations and comparing results between the decades 2001-2010 and 2011-2020, the study unveils critical insights into groundwater dynamics. Points such as 15 exhibit pronounced risk increases,

indicating potential overexploitation or insufficient replenishment. Notably, certain points display decreasing risks, showcasing positive trends that align with effective groundwater management practices.

This comprehensive probabilistic approach provides valuable information for stakeholders, empowering them to make informed decisions in selecting a sustainable energy source.

1 Introduction

In the next 30 years, the global population is expected to increase by 2.5 billion. As a result, the demand for power, particularly in the construction industry, will soar. This will result from an increasing number of households (Koulamas et al. 2018). Power consumption in residential buildings is mainly driven by heating and cooling the rooms, preparing hot water, lighting and the use of equipment (Cao et al. 2016). According to the statistics of the International Energy Agency IEA (Calero et al. 2018), the most power is consumed for heating rooms in this sector.

There are numerous technologies available on the market that may help reduce energy consumption in buildings. They are easily available. Some of the examples are heat pumps (Biglia et al.2021; Ceglia et al.2022; Gizzi et al., 2023), photovoltaic systems (Liu et al., 2019), highly-efficient windows (Lago et al., 2019; Lami et al., 2023), thermal insulation of buildings (Aslan 2022; Ozbek et al., 2022), energy-efficient fittings and equipment and effective control (Potočnik et al., 2018; Aguilera et al., 2019).

Heat pumps may play the key role in implementing technologies that produce clean energy (International Energy Agency, 2022). This concept has been confirmed by recent reviews of buildings with near-zero power consumption that covered the whole territory of Europe. This research demonstrated that heat pumps are the essential technology for cost-optimised solutions in designing residential buildings (Thonipara et al., 2019). Heat pumps may obtain energy from many various sources. As far as ground heat pumps are concerned, energy is obtained from the ground (Greco et al., 2022) ground waters (Zhao et al., 2022) surface waters (Kindaichi et al. 2015; Jung et al. 2022) and sediment rocks (Han and Yu 2016). Ground waters may be utilised both in open systems, where water is the energy carries, and in closed systems, where the exchanger is installed in waterlogged formations or rock masses (Sanner 2001; Mazurkiewicz 2015). Ideally, the operation of ground source heat pumps is more predictable than that of air-water or air-air pumps. Unfortunately, their installation is often subject to limitations that result from land characteristics, as well as geological and hydrogeological conditions. The uncertainty in estimating the efficiency of such systems at the design stage remains high and depends on multiple factors, including the accessibility of ground waters (Biglia et al., 2021).

In the 20th century, we witnessed a rapid development in drilling for various purposes, including to generate power, both in urban or suburban and rural areas. The development in the technology of drilling and pumping ground waters and the constant access to energy to power the pumps influenced the development of this source of water (International Association of Hydrogeologists 2015, 2019). Unfortunately, it should be noted that ground waters are usually a poorly managed and

https://doi.org/10.5194/hess-2024-41
Preprint. Discussion started: 14 March 2024

Hydrology and Earth System Sciences
Discussions

insufficiently protected resource, which results in periodical ground water deficits in some regions that are particularly vulnerable to droughts (International Association of Hydrogeologists 2015, 2019). Droughts in the 21st century are different from those in the previous centuries. They usually last longer, affect larger areas, and are accompanied by higher temperatures. The natural course of droughts became more severe as a result of the growing demand for water, increasing anthropogenic pressure, and climate changes. The prognoses of the European Environment Agency show that in the years 2041-2070, the frequency of droughts, primarily meteorological droughts, followed by hydrological and hydrogeological ones, will increase nearly in all Europe, including in Poland (European Environment Agency. 2019; Tokarczyk 2020)

Wide access to data enables conducting very advanced research on droughts (Li and Rodell 2021), their influence on the resources and quality of ground waters, and the health of their users (Kubicz et al., 2021). 2022). Scientific research offers a possibility to predict ground water deficits with a high level of accuracy (Kajewska-Szkudlarek et al., 2022). However, at the same time, these data are not easily accessible and comprehensible for their potential users. Due to that, the authors of this study propose a relatively simple method to assess and visually present the risk of deficit of ground waters that may be used as an energy source in the heat pump system. The method allows to create colourful information boards that show the seasons of the year in which the level of the ground waters in the vicinity of the given well may significantly decrease. Additionally, the method offers the possibility to monitor the changes in the risk of the lowering of the ground water level in the area in a predefined observation period.

During droughts, the water level in the aquifer may decrease significantly. This results in reduced accessibility of ground waters (Van Loon 2015). In consequence, the amount of energy that the heat pump may obtain, is limited, which may lower its efficiency. One should also bear in mind that the system will have to work harder in order to extract the power from the ground. If, as a result of the drought, the temperature of ground waters increases more than usually, this might lead to overheating the installation, which, in turn, may reduce the efficiency and lead to damages (Dehkordi and Schincariol 2014).

It should be emphasised clearly that exceeding certain critical values of the ground water level position may lead to the destruction of the infrastructure of the well that is an element of the heat pump system, and damage the aquifer from which water, and thus also energy, is obtained, As a result of excessive lowering of the ground water level, the quality of the water flowing into the well is deteriorating: it contains sand or mud and has poor quality parameters that have an adverse influence on the installed equipment. Apart from that, the efficiency of the well decreases, depression grows, and, in consequence, the operating costs of the well are increasing. The most common adverse effect in intensively exploited wells is chemical clogging that is caused by erosion processes and results from the emergence of chemical compounds such as calcium carbonates and iron oxides. Mechanical clogging, connected to the suffusion phenomenon, also takes place. Grains of soil clog the pores of the primary sediment, if their granulation is adequate. Chemical clogging usually occurs on the well filter, and, more precisely, its active elements. On the other hand, mechanical clogging usually affects the zone near to the hole, causing an obstruction of the well hole (Polak and Kaznowska-Opala Karolina 2018). Excessive exploitation of a well may lead to damaging the filter and so-called sanding. Penetration of solid particles into the well results in accelerated rate of wear of pump elements and the

https://doi.org/10.5194/hess-2024-41
Preprint. Discussion started: 14 March 2024

Hydrology and Earth System Sciences
Open Access
EGU
Discussions

settlement of rock layers, and, in consequence, uneven load on the technical column. As a result, the hydraulic jump increases, which leads to hydraulic loss and, finally, to reduced hydraulic efficiency of the well (Driscoll 1986; Houben 2007).

The presented method does not use the well-known indicators of hydrogeological drought, such as the Reconnaissance Drought Index (RDI), Standardized Runoff Index (SRI), Standardized Subsurface Runoff Index (SSRI), and Standardized Groundwater level Index (SGI) that are used to identify particularly sensitive areas (Kubicz and Bąk 2019; Guo et al., 2021; Babre et al., 2022). It is simple, as it relies on a small amount of input data for calculations, which is very important in engineering practice. The historical data about the ground water level in the given region are sufficient. The method requires neither a specific description of drought or ground water deficit nor the detailed characteristics of the factors that influence it, e.g. precipitation, evapotraspiration, temperature, volume of exploitation of ground waters or the lack thereof. It should be noted that the phenomenon of fluctuations in ground water levels in itself is characterised by certain randomness in itself, and the method discussed here, based on the probabilistic model, enables to take it into account.

2 Method

The proposed method to assess the risk of extreme lowering of the groundwater table consists in calculating the probability based on statistically matched theoretical data distributions.

The distribution functions of the empirical and theoretical distributions of the minima were drawn based on selected sets of values of the minimum levels of groundwaters. The minimum levels of groundwaters were analysed with the use of the probability distributions that are traditionally applied in hydrogeology, as presented in Table 1 (Rutkowska and Ptak 2012; Cammalleri et al., 2022). Before the estimation, a stationarity test was conducted. Then, the ADF (Augmented Dickey–Fuller) test was used for this purpose (Said and Dickey1984) . In this way, it was assessed whether the factors that determine the course of the described phenomenon remain constant and stable at the given point during the study.

Table 1: Distribution functions of selected probability distributions

Probability distribution	Distribution function *F(X)*
Normal $N(\mu, \sigma^2)$	$\frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right]$ (1)
Weibull $W(\lambda, k)$	$1 - e^{-(x/\lambda)^k}$ $x \geq 0$ (2)
Log-normal $LN(\mu, \sigma^2)$	$\frac{1}{2}\left[1 + erf\left(\frac{ln(x)-\mu}{2\sigma^2}\right)\right]$ (3)
Gamma $G(\theta, k)$	$\frac{1}{\Gamma(k)}\gamma\left(k, {}^{x}/_{\theta}\right)$ (4)
Weibull 3-parametric $W(\lambda, k, \gamma)$	$1 - e^{-((x-\gamma)/\lambda)^k}$ $x \geq 0$ (5)

https://doi.org/10.5194/hess-2024-41
Preprint. Discussion started: 14 March 2024

Hydrology and Earth System Sciences
Discussions
Open Access

Due to the high number of factors that influence the form of distribution of minimum groundwater levels, several distributions should be applied each time when tests are conducted for various observation points, in order to find the one that will best reflect the empirical distribution of the analysed parameter.

At the next stage, the selected models with the estimated parameters were used to assess the extreme lowering of groundwater level at the analysed test points in specific periods. The best matched distribution was selected based on tests of the conformity of the empirical distribution of semi-annual minimum groundwater levels with the theoretical distributions. The Anderson-Darling test was conducted (Anderson and Darling 1952; Jäntschi and Bolboacă 2018). This test is sensitive to the conformity of distributions in their tails, which define the extreme phenomena to a great extent.

Probability, which plays the role of a measure of risk of the extreme lowering of groundwater level, was calculated from the formula:

$$P(M) = 1 - G_{min}(x_{h_{kr}}) \qquad (6)$$

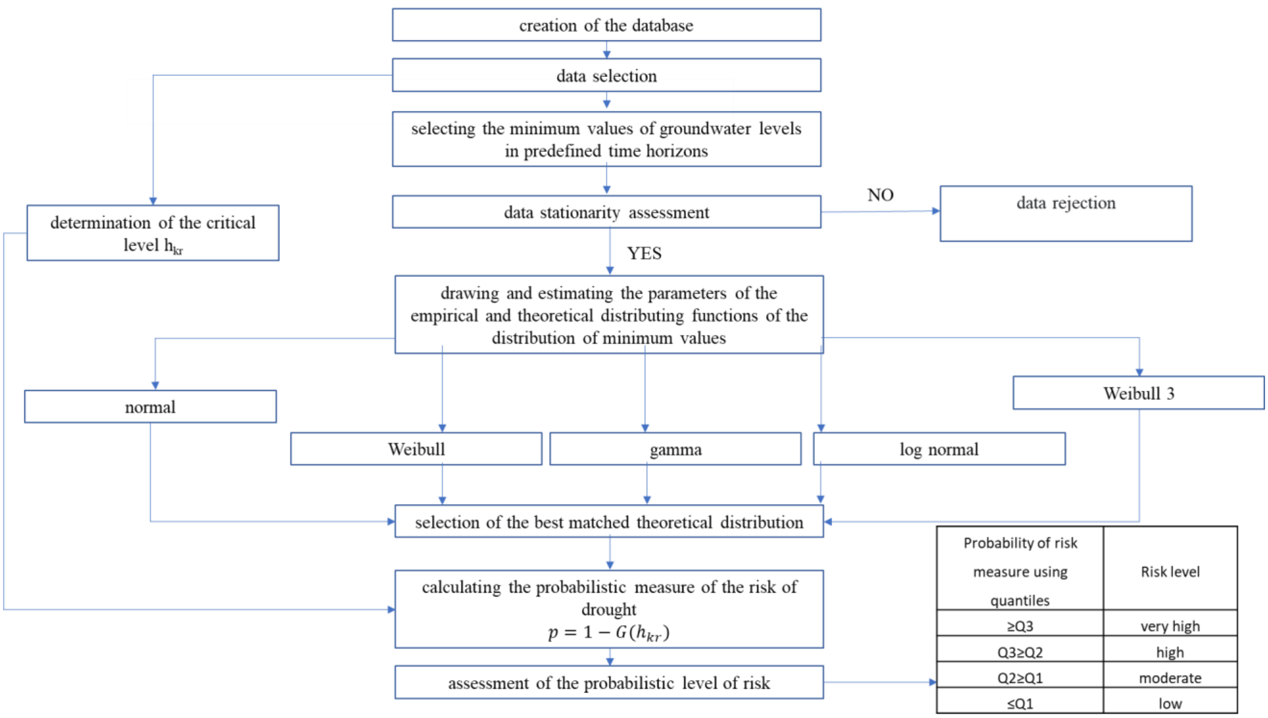
where:

$M = \min(x_1, x_2, \ldots, x_i)$, $x_1, x_2, \ldots, x_i$ – water level values observed once a week during a half-year period,

$x_{h_{kr}}$ – value of the level that exceeds the critical threshold of groundwater level for the analysed test point,

G_{min} – theoretical distribution function of the minimum values of semi-annual groundwaters level.

For the purposes of the present study, four risk levels were distinguished: very high, high, moderate, low. As a result, a procedure was developed to estimate the probabilistic measure of the risk. It consists of the following steps (Figure 1)



https://doi.org/10.5194/hess-2024-41
Preprint. Discussion started: 14 March 2024

Hydrology and Earth System Sciences Discussions

Figure 1: Methodological scheme of estimate the probabilistic measure of the extreme lowering of groundwater level.

3 Study area and data

3.1 Geological and hydrogeological setting

The analysed area is situated in the north-western part of the Eurasian continent (Babre et al., 2022). At larger depths, Mesozoic and Palaeozoic sediments and folds are present, which were then covered by a thick layer of Cenozoic sediments that originate from alluvial, wind-related, and glacial accumulation. The topmost, Quaternary sediments, contain large amount of material of Scandinavian origin. These are fragments of crushed crystalline and sediment rocks and mineral fragments (clay, gravel, and sand) (Polish Geological Institute National Research Institute (Poland) et al.)

Figure 2: Location of measurements points·measurement points ©OpenStreetMap Distributed under the Open Data Commons Open Database License 1.0 (ODbL 1.0).

3.2 Data

The risk assessment was conducted for 27 observation points of groundwaters (which are characterised in detail in Table 2 and shown in Figure 2). For the purposes of this article, one of the hydrometric parameters, i.e. the level of groundwaters, was

https://doi.org/10.5194/hess-2024-41
Preprint. Discussion started: 14 March 2024

analysed. The authors used the measurements of the level of the groundwater table from the years 1980-2020, which were obtained from the database of the Polish Geological Institute – National Research Institute. The data were not treated as a temporal series, so gaps, if they existed or if the measurements in the given point started at a later time, were not completed. One month, three months and semi-annual (including summer and winter), and decades 2001-2010 and 2011-2020 minima were selected from the full database, according to the following assumption:

$$y_i = \min\{ x_{i1}, \ldots, x_{im}\}, \qquad i = 1,\ldots, n. \qquad (7)$$

The critical level h_{kr} was calculated for each measurement point. It was assumed that, if the water table level falls below that value, we are certainly dealing with groundwater drought. For the purposes of our analyses, h_{kr} corresponding to the 70th and 90th percentile was used (hereinafter denoted as $h_{kr=70perc.}$ and $h_{kr=90perc.}$). provided that the h_{kr} level may be selected individually.

Table 2 Basic information about the measurements.

No of point	Location	Type of groundwater table	Type of well	Elevation point [m a.s.l.]	Depth to the drilled groundwater table [m b.g.l.]	Depth to the established groundwater table [m b.g.l.]	Depth to the bottom of the aquifer [m b.g.l.]	Depth to the top of the aquifer [m b.g.l.]	Stratygraphy	Lithology	Type of ground	Location in the major groundwater reservoir
1	Sarbicko - 1	confined	drilled well	115.46	32	6	100	32	K2	marl	porous-crevice	+
2	Sarbicko - 2	unconfined	drilled well	115.12	5.37	5.37	29	5.37	Q	sands	porous	+
3	Czachurki	unconfined	drilled well	121.25	0.8	0.8	8.5	0.8	Q	sands and gravels	porous	+
4	Szubin	confined	drilled well	71.5	14	4	43	14	Q	sands	porous	-
5	Chachalnia	unconfined	piezometer	161.5	5.9	5.9	20	5.9	Q	gravels and sands	porous	-
6	Bogdaszowice	confined	piezometer	134.5	10	6.5	89	10	Q	medium-grained sands	porous	+
7	Złoty Potok	unconfined	piezometer	314.24	8	8	18	8	J3+Q	sands	porous	+
8	Żółwia Błoć	confined	drilled well	30	14	1.84	58	14	Q	sands	porous	+

https://doi.org/10.5194/hess-2024-41
Preprint. Discussion started: 14 March 2024

Hydrology and Earth System Sciences
Discussions

9	Gądno	confined	drilled well	60	20	12.3	48	20	Q	sands and gravels	porous	-
10	Międzyzdroje	unconfined	drilled well	36.3	31.8	31.8	72	31.8	Q	sands	porous	+
11	Koszewko	unconfined	piezometer	25.96	5.9	5.9	15.3	5.9	Q	sands and gravels	porous	-
12	Dobrzyń	unconfined	piezometer	133.72	3.81	3.81	13	3.81	Q	sands and gravels	porous	+
13	Lasów	unconfined	drilled well	173.1	4	4	24	4	Q	gravels	porous	-
14	Spore	unconfined	piezometer	138.5	2.9	2.9	4.1	2.8	Q	sands	porous	+
15	Borówiec	confined	drilled well	82.67	89	10.78	118	89	NgM	sands	porous	+
16	Głazów	confined	drilled well	66	18.5	4.15	32	18.5	Q	sands	porous	-
17	Jaskrów	unconfined	piezometer	253.7	17.5	17.5	30	17.5	J3	limestone	crevice-karstic	+
18	Radolin	unconfined	drilled well	74.14	31.28	31.28	55	31.28	NgM+Q	sands	porous	+
19	Kamieńsk	unconfined	drilled well	225.86	13.1	13.1	87.1	13.1	K2	limestone	porous-crevice	+
20	Kochcice	confined	drilled well	278.45	15	14	20	15	Q	sands	porous	+
21	Murzynowo	unconfined	drilled well	30	8	8	30.5	8	Q	sands and gravels	porous	-
22	Słońsk	unconfined	drilled well	19.07	6	6	30	6	Q	sands	porous	-
23	Ujście	unconfined	drilled well	62.21	13	13	30	13	Q	sands	porous	+
24	Stęszew	unconfined	well	74.96	4.72	4.72	8.1	4.72	Q	sands and gravels	porous	+
25	Międzychód	confined	drilled well	42.58	11.2	6	16	11.2	Q	gravels	porous	+
26	Turowo	unconfined	drilled well	158.96	5.95	5.95	20	5.95	Q	sands	porous	+
27	Dźwirzyno	confined	drilled well	2.79	19.5	2.25	25	19.5	Q	gravels	porous	-

The ADF test was used to confirm or deny the assumption about data stationarity, i.e. the stability of distribution parameters with time. Based on that, 17 points were selected for further analysis (Table 4). Ten points did not meet the stationarity criterion. The possibility to use the distribuants of the data distributions to calculate the risk of occurrence of hydrogeological droughts was confirmed for the following points: 1 – Sarbicko-1, 2 – Sarbicko-2, 3 – Czachurki, 4 – Szubin, 5- Chachalnia, 6 -Bogdaszowice, 7 – Złoty Potok, 8 – Żółwia Błoć, 9 - Gądno, 10 – Międzyzdroje, 11 – Koszewko, 13 – Lisów, 15 – Borówiec, 17 – Jaskrów, 19 – Kamieńsk, 20 – Kochcice, 23 – Ujście. The best match of the analysed theoretical distributions to the analysed empirical distributions for the analysed periods was estimated with the use of the previously described Anderson-Darling test. The results of the stationarity analysis are presented in Table 3, and the percentage of allocation to selected distributions is shown in Figure 3.

Table 3 Results of data stationarity analysis - ADF test.

No of point	Location	Result of ADF test	No of point	Localisation	ADF test
1	Sarbicko - 1	stationary	15	Borówiec	stationary
2	Sarbicko - 2	stationary	16	Głazów	non-stationary
3	Czachurki	stationary	17	Jaskrów	stationary
4	Szubin	stationary	18	Radolin	non-stationary
5	Chachalnia	stationary	19	Kamieńsk	stationary
6	Bogdaszowice	stationary	20	Kochcice	stationary
7	Złoty Potok	stationary	21	Murzynowo	non-stationary
8	Żółwia Błoć	stationary	22	Słońsk	non-stationary
9	Gądno	stationary	23	Ujście	stationary
10	Międzyzdroje	stationary	24	Stęszew	non-stationary
11	Koszewko	stationary	25	Międzychód	non-stationary
12	Dobrzyń	non-stationary	26	Turowo	non-stationary
13	Lasów	stationary	27	Dźwirzyno	non-stationary
14	Spore	non-stationary			

https://doi.org/10.5194/hess-2024-41
Preprint. Discussion started: 14 March 2024

Hydrology and Earth System Sciences
Discussions

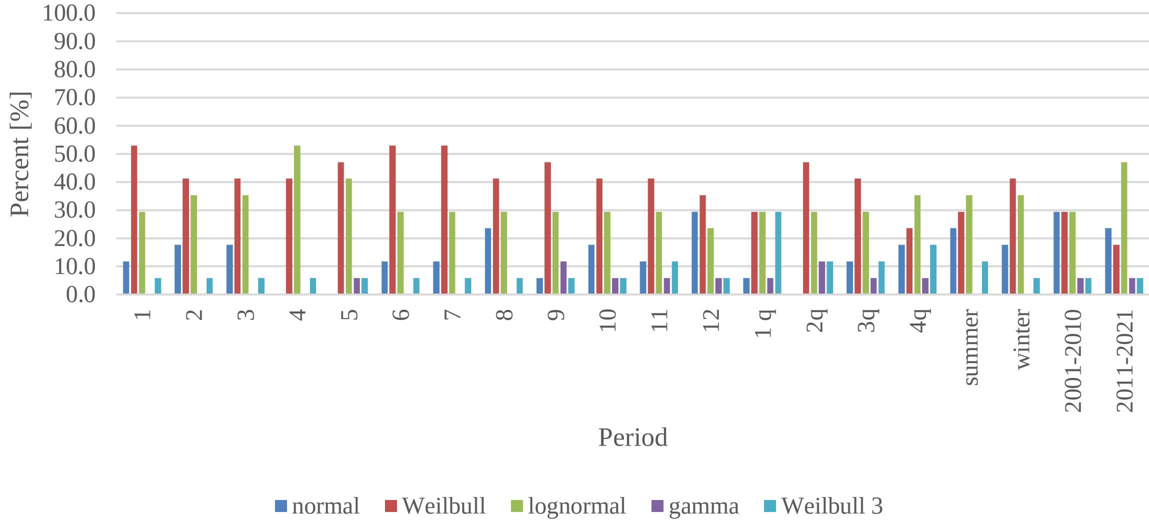


Figure 3: Percentage of best-matched theoretical distributions in different periods (1-12 – months, 1q-4q – quarter of year, summer, winter - summer, winter half-year, decades 2001-2010 and 2011-2020.

4 Results and discussion

Tables 4 and 5 show the results of the assessment of the risk of the groundwater levels decreasing below $h_{kr=70perc}$ and $h_{kr=90perc}$, for points that met the previously described criteria. The presented form of analysis and its result provide unchanging information that is referred to historical conditions but is very important for users and managers of groundwaters.

Quantiles were used to divide the calculated values of the probability of exceeding the critical value $P_{h_{kr}}$, into four risk groups: very high risk (≥Q3), high risk (Q3≥Q2), medium risk (Q2≥Q1), and low risk (≤Q1).

In this way, clear information about the threat of lowering of the groundwater table in the analysed periods was obtained. The analyses were conducted in two variants. In the first variant, the risk of the groundwater table decreasing below hkr was calculated, for specific months, quarters, and hydrological seasons (summer and winter). In the second variant, the change in the level of risk in two consecutive decades: 2001-2010 and 2011-2020 was analysed.

The risk analysis that assumed the h_{kr} to be the value of the 70th percentile (Table 4), demonstrated that the points that were the most endangered in the annual scale were points 17 and 23. In point 23, the risk of excessive lowering of the groundwater level remained high in all months with the exception of June. For point 17, seven months were classified to the group of high risk of decreasing table of groundwaters, while in the other five months the risk was medium. Observation point 10 should be noted, as in August, September, and October very high risk was recorded there. However, point 10 is also exceptional, because from January until May, the risk of a decrease in groundwater level below the 70th percentile is low. A high level of risk is also characteristic for November in point 13. On the other hand, the lowest risk level on an annual scale was noted in point 11, where the level of risk fell into the low-risk group for eight months of the year. As for the risk of a decrease in the level of

https://doi.org/10.5194/hess-2024-41
Preprint. Discussion started: 14 March 2024

groundwaters below h_{kr}=$_{90\ perc.}$ (Table 5), observation point 15 is remarkable. In the period from July to December, it was characterised by a high level of risk of groundwaters decreasing below $h_{kr.}$ In points 10 and 13, a very high risk level was observed only in certain months. In point 10, very high risk was characteristic only for late summer (August-September), while in point 13 for autumn (October-November). The lowest level of risk of a decrease in the groundwater table below the 90th percentile was noted in point 11.

The risk assessment may also be referred to quarterly data, which confirm the results of the analysis for monthly data. However, the assessment in terms of hydrological seasons leads to the loss of a large amount of information, so it is not recommended. Tables 4 and 5 demonstrate that the results presented in this was show the level of risk very clearly.

Table 4: The result of estimate the probabilistic measure of the extreme lowering of groundwater level for $h_{kr=70perc.}$

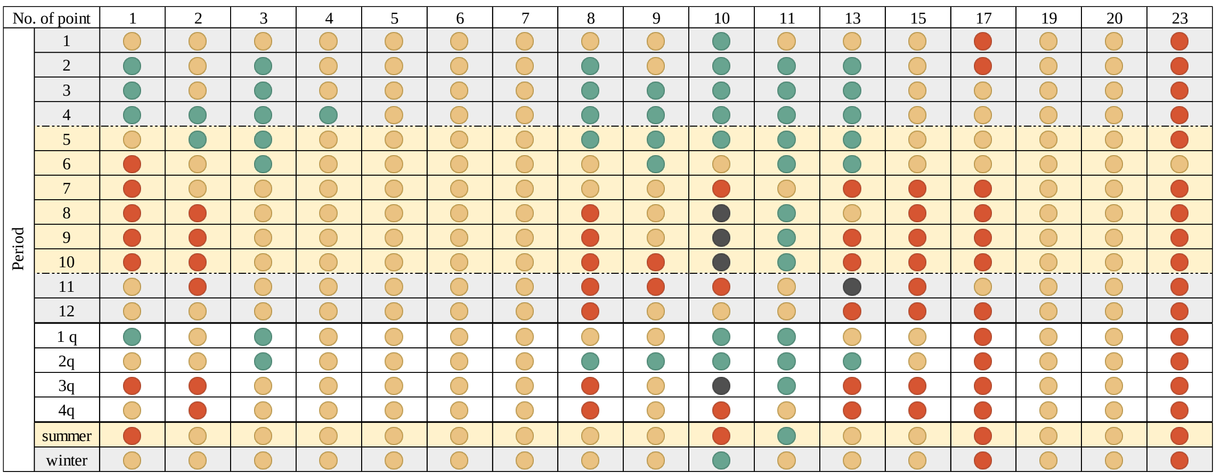


Table 5: The result of estimate the probabilistic measure of the extreme lowering of groundwater level for $h_{kr=90perc.}$

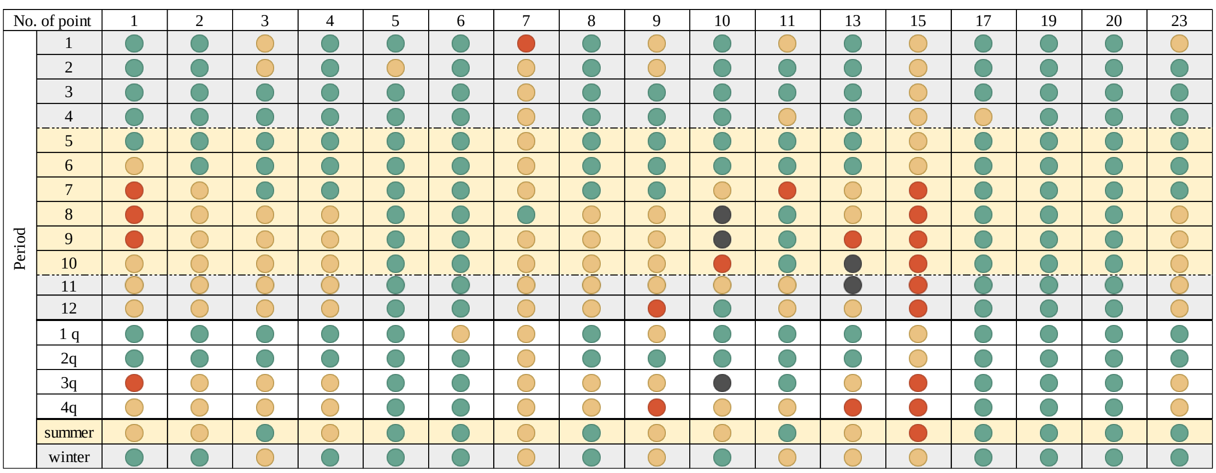


Table 6: The result of estimate the probabilistic measure of the extreme lowering of groundwater level for $h_{kr=70perc.}$ and $h_{kr=90perc.}$ in decades 2001-2010 and 2011-2020.

https://doi.org/10.5194/hess-2024-41
Preprint. Discussion started: 14 March 2024

Hydrology and Earth System Sciences
Open Access
Discussions

		No. of point	1	2	3	4	5	6	7	8	9	10	11	13	15	17	19	20	23
Period	h_{kr} 70 percentile	2001-2010	green	green	yellow	green	green	green	green	yellow	yellow	dark	yellow	yellow	green	green	green	green	dark
		2011-2020	yellow	yellow	red	dark	yellow	yellow	yellow	yellow	green	yellow	green	yellow	dark	green	green	red	green
	h_{kr} 90 percentile	2001-2010	green	green	green	green	green	green	green	green	green	yellow	green	yellow	green	green	green	green	dark
		2011-2020	yellow	yellow	red	red	yellow	green	yellow	green	green	green	green	green	dark	green	green	green	green

The risk assessment for the consecutive decades 2001-2010 and 2011-2020 is presented in Table 6. This structure of the results database provides a synthetic overview of the risk of lowering of the groundwater table below $h_{kr.}$ The highest risk increase in reference to $h_{kr= 70\ perc.}$, between decades was noted in points 4 and 15, while point 20 was characterised by a slightly lower risk increase. As far as $h_{kr}=$ $_{90\ perc.}$ is concerned, the highest risk increase was noted for point 15, whereas in points 3 and 4 it was slightly lower. This information is very important for water users, as it indicates that the water resources in the analysed aquifer may be overexploited or that the level of supply is too low, which might negatively influence their accessibility and energy acquisition. However, analysis conducted in such way may also reveal some positive changes: a significant decrease in the risk was noted for points 10 and 23.

The combination of information about the risk in specific months or quarters with the data related to the increase or decrease in risk in the consecutive decades makes it necessary to distinguish point 15 and have a closer look at it. In one half of the year, this point is classified as a point with high risk of lowering the water table below $h_{kr=70perc}$ and $h_{kr=90perc}$ and in the second half of the year it is characterised by medium risk. Unfortunately, the analysis of changes in risk revealed that in the consecutive decades the risk increased for both h_{kr} values from low to very high level. This means that the water resources in the area require special control. On the other hand, it is positive that point 23, which is characterised by a high risk of lowering the water level below the 70th percentile in specific months, shows that the risk has lowered in the consecutive decades. In the years 2001-2010 the risk was very high, whereas in 2011-2020 it was classified as low. A similar phenomenon was noted for point 10. Based on observations from the late summer and early autumn, it was assigned to the category of points of very high risk of excessive decrease in the groundwater level. However, the analysis of consecutive decades showed some positive trends. The risk decreased from very high to medium for $h_{kr=70perc}$. and from medium to low for $h_{kr=90perc}$.

In order to verify the accuracy of the obtained results, the authors sought information that would confirm or deny these results for several observation points. The query of available data on aquifers confirmed the increasing risk of groundwater shortage in point 15, in the town Borówiec. According to the data of the National Geological Institute – National Research Institute (PIG-PIB), the table of groundwaters of the observed level has been lowering systematically since the 1990s, with a tendency to slow down the decrease in wet years and during the winter half-years.

The above phenomenon indicated that the exploitation of waters exceeded the renewability of the level and that the stored resources were being depleted (Dąbrowski S et al., 1997). The tests conducted in point 10 in Międzyzdroje refer to the Quaternary aquifer layer. It is important for the region from the economic point of view, because its waters are used by all water supply and local (private) water intakes (2018). The query of available materials confirmed the results of the present analysis. The risk of excessive lowering of the groundwater level in point 10 is decreasing. Limiting the exploitation of concentrated groundwater intakes, the construction of scattered intakes, and strict monitoring of the collected water had a positive influence on the risk of groundwater shortage in the scale of a decade (Gurwin and Krawiec 2012). Periodical problems with water supply in the summer season result from increasing water supply to satisfy the needs of hotels and holiday resorts. The region of Międzyzdroje is a strongly developed tourist area, which is particularly noticeable in July, August, and September (2018). On the other hand, point 23 is located in the area of Kujawy, i.e. the part of Poland where droughts and their effects are observed the most frequently. The aquifer that is present here has been thoroughly analysed. In spite of the unconfined water table, it does not respond to precipitation shortages. The drill is situated in the direct vicinity of the catchment of the Gwda River, in a valley landscape. Due to the fact that the observation well is located in the catchment, the aquifer is supplied mainly by the inflow of water from interbedding aquifers, and by waters emerging from deeper aquifer layers (Jamorska et al., 2019). This allows the groundwater level to fall below hkr=70perc, and, at the same time, it prevents the level from decreasing below hkr=90perc.

5 Conclusions

The method presented in the article is based on statistical analysis. The probability of extreme lowering of the groundwater level was assessed based on the theoretical data distributions that were determined first of all. Then, with the use of conformity tests, the best matched distributions were selected, which were the basis for assessing the risk. The risk assessment results were presented in form of easily legible tables. The authors presented risk assessment results for individual measurement points, taking into account the proposed risk ranges (very high, high, moderate, low) and periods (months, quarters, half-years, and decades). The analyses were conducted in the basing of the Oder River, in the north-western part of the Eurasian continent, and took into account aquifers of various characteristics.

In conclusion, the paper presents a method of analysing the risk of extreme lowering of the groundwater levels, which may be helpful for users, engineers, and managers of groundwaters in the context of their sustainable use. The visual system that supports users of groundwaters in form of tables with coloured markings that was proposed here may facilitate the process of making decisions related to the installation, operation, and efficiency of heat pumps.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.
Competing Interests The authors have no relevant financial or non-financial interests to disclose.
Acknowledgements This document is based on data provided by the Polish Geological Institute.
Authors contribution Justyna Kubicz - conceptualization, methodology, writing–original draft preparation, validation (75%) ; Maciej Karczewski – calculations, validation (25%). All authors read and approved the final manuscript.

References

Aguilera JJ, Kazanci OB, Toftum J (2019) Thermal adaptation in occupant-driven HVAC control. Journal of Building Engineering 25:100846. https://doi.org/10.1016/J.JOBE.2019.100846

Anderson TW, Darling DA (1952) Asymptotic Theory of Certain "Goodness of Fit" Criteria Based on Stochastic Processes. The Annals of Mathematical Statistics 23:. https://doi.org/10.1214/aoms/1177729437

Aslan A (2022) Effect of thermal insulation on building energy efficiency in Turkey. Proceedings of Institution of Civil Engineers: Energy 175:119–139. https://doi.org/10.1680/JENER.21.00053

Babre A, Kalvāns A, Avotniece Z, et al (2022) The use of predefined drought indices for the assessment of groundwater drought episodes in the Baltic States over the period 1989–2018. J Hydrol Reg Stud 40:. https://doi.org/10.1016/j.ejrh.2022.101049

Biglia A, Ferrara M, Fabrizio E (2021) On the real performance of groundwater heat pumps: Experimental evidence from a residential district. Appl Therm Eng 192:116887. https://doi.org/10.1016/J.APPLTHERMALENG.2021.116887

Calero M, Alameda-Hernandez E, Fernández-Serrano M, et al (2018) Energy consumption reduction proposals for thermal systems in residential buildings. Energy Build 175:121–130. https://doi.org/10.1016/J.ENBUILD.2018.07.028

Cammalleri C, Spinoni J, Barbosa P, et al (2022) The effects of non-stationarity on SPI for operational drought monitoring in Europe. International Journal of Climatology 42:3418–3430. https://doi.org/https://doi.org/10.1002/joc.7424

Cao X, Dai X, Liu J (2016) Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. Energy Build 128:198–213. https://doi.org/10.1016/J.ENBUILD.2016.06.089

Ceglia F, Marrasso E, Roselli C, et al (2022) Exergetic and exergoeconomic analysis of an experimental ground source heat pump system coupled with a thermal storage based on Hardware in Loop. Appl Therm Eng 212:118559. https://doi.org/10.1016/J.APPLTHERMALENG.2022.118559

Dąbrowski S. Przybyłek J. Górski J Subregion Warty nizinnej. In: Hydrogeologia regionalna Polski. Wody słodkie, . PIG, Warszawa

Dąbrowski S, Trzeciakowska M, Dragon K (1997) Mapa hydrogeologiczna Polski w skali 1:50 000 Arkusz KÓRNIK (508). Warszawa

Dehkordi SE, Schincariol RA (2014) Effect of thermal-hydrogeological and borehole heat exchanger properties on performance and impact of vertical closed-loop geothermal heat pump systems. Hydrogeol J 22:189–203. https://doi.org/10.1007/s10040-013-1060-6

Driscoll FG (1986) Groundwater and wells. Johnson Division

European Environment Agency. (2019) The European environment—State and outlook 2020: Knowledge for transition to a sustainable Europe. Luxembourg

Gizzi M, Vagnon F, Taddia G, Lo Russo S (2023) A Review of Groundwater Heat Pump Systems in the Italian Framework: Technological Potential and Environmental Limits. Energies (Basel) 16:4813. https://doi.org/10.3390/en16124813

https://doi.org/10.5194/hess-2024-41
Preprint. Discussion started: 14 March 2024

Greco A, Gundabattini E, Solomon DG, et al (2022) A Review on Geothermal Renewable Energy Systems for Eco-Friendly Air-Conditioning. Energies 2022, Vol 15, Page 5519 15:5519. https://doi.org/10.3390/EN15155519

Guo M, Yue W, Wang T, et al (2021) Assessing the use of standardized groundwater index for quantifying groundwater drought over the conterminous US. J Hydrol (Amst) 598:126227. https://doi.org/10.1016/J.JHYDROL.2021.126227

Gurwin J, Krawiec A (2012) Identyfikacja krążenia wód podziemnych na wyspie Wolin

Han C, Yu XB (2016) Performance of a residential ground source heat pump system in sedimentary rock formation. Appl Energy 164:89–98. https://doi.org/10.1016/J.APENERGY.2015.12.003

Hoc R, Jezierski P (2027) Region Zachodniopomorski. In: Hydrogeologia regionalna Polski. PIG, Warszawa

Houben G, TC (2007) Water Well Rehabilitation and Reconstruction. McGraw Hill, New York

International Association of Hydrogeologists (2015) Why is groundwater critical for urban water-supply security ? Strategic Overview Series KEY MESSAGES

International Association of Hydrogeologists (2019) Why are groundwater systems and aquifer storage of major importance for climate-change adaptation ? CLIMATE-CHANGE ADAPTATION & GROUNDWATER Strategic Overview Series KEY MESSAGES

Jamorska I, Kubiak-Wójcicka K, Krawiec A (2019) Dynamics of the status of groundwater in the Polish Lowland: The River Gwda catchment example. Geologos 25:. https://doi.org/10.2478/logos-2019-0021

Jäntschi L, Bolboacă SD (2018) Computation of probability associated with Anderson-Darling statistic. Mathematics 6:. https://doi.org/10.3390/math6060088

Jung Y, Oh J, Han U, Lee H (2022) A comprehensive review of thermal potential and heat utilization for water source heat pump systems. Energy Build 266:112124. https://doi.org/10.1016/J.ENBUILD.2022.112124

Kajewska-Szkudlarek J, Kubicz J, Kajewski I (2022) Correlation approach in predictor selection for groundwater level forecasting in areas threatened by water deficits. Journal of Hydroinformatics 24:143–159. https://doi.org/10.2166/HYDRO.2021.059

Kindaichi S, Nishina D, Wen L, Kannaka T (2015) Potential for using water reservoirs as heat sources in heat pump systems. Appl Therm Eng 76:47–53. https://doi.org/10.1016/J.APPLTHERMALENG.2014.10.091

Koulamas C, Kalogeras AP, Pacheco-Torres R, et al (2018) Suitability analysis of modeling and assessment approaches in energy efficiency in buildings. Energy Build 158:1662–1682. https://doi.org/10.1016/J.ENBUILD.2017.12.002

Kubicz J, Bąk B (2019) The reaction of groundwater to several months' meteorological drought in Poland. Pol J Environ Stud 28:187–195. https://doi.org/10.15244/pjoes/81691

Kubicz J, Lochyński P, Pawełczyk A, Karczewski M (2021) Effects of drought on environmental health risk posed by groundwater contamination. Chemosphere 263:128145. https://doi.org/10.1016/J.CHEMOSPHERE.2020.128145

Lago TGS, Ismail KAR, Lino FAM (2019) Ventilated double glass window with reflective film: Modeling and assessment of performance. Solar Energy 185:72–88. https://doi.org/10.1016/J.SOLENER.2019.04.047

https://doi.org/10.5194/hess-2024-41
Preprint. Discussion started: 14 March 2024

Lami M, Al-naemi F, Jabbar HA, et al (2023) Optimisation of wasted air utilisation in thermal loss reduction in double-glazed windows of commercial buildings in cold regions. International Journal of Energy and Environmental Engineering 14:145–165. https://doi.org/10.1007/S40095-022-00499-0/FIGURES/14

Li B, Rodell M (2021) Groundwater drought: environmental controls and monitoring. Global Groundwater 145–162. https://doi.org/10.1016/B978-0-12-818172-0.00011-6

Liu J, Chen X, Cao S, Yang H (2019) Overview on hybrid solar photovoltaic-electrical energy storage technologies for power supply to buildings. Energy Convers Manag 187:103–121. https://doi.org/10.1016/J.ENCONMAN.2019.02.080

Mazurkiewicz J (2015) Główne bariery rozwoju geotermii niskotemperaturowej wspomaganej pompami ciepła typu woda/woda w Polsce. GAZ, WODA I TECHNIKA SANITARNA 2:

Ozbek K, Gelis K, Ozyurt O (2022) Optimization of external wall insulation thickness in buildings using response surface methodology. International Journal of Energy and Environmental Engineering 13:1367–1381. https://doi.org/10.1007/S40095-022-00490-9/TABLES/9

Państwowy Instytut Geologiczny - Państwowy Instytut Badawczy (Poland), Nawrocki J (Geologist), Becker A Atlas geologiczny Polski

Polak K, Kaznowska-Opala Karolina (2018) GÓRNICTWO ODKRYWKOWE nr 2/2018 63

Potočnik P, Vidrih B, Kitanovski A, Govekar E (2018) Analysis and optimization of thermal comfort in residential buildings by means of a weather-controlled air-to-water heat pump. Build Environ 140:68–79. https://doi.org/10.1016/J.BUILDENV.2018.05.044

Rutkowska A, Ptak M (2012) On Certain Stationarity Tests for Hydrologic Series. Studia Geotechnica et Mechanica 34:51–63. https://doi.org/doi:10.1515/sgem-2017-0022

Said SE, Dickey DA (1984) Testing for unit roots in autoregressive-moving average models of unknown order. Biometrika 71:599–607. https://doi.org/10.1093/biomet/71.3.599

Sanner B (2001) SHALLOW GEOTHERMAL ENERGY

Staśko S., Kowalczyk A., Rubin H., Rubin K. (2007) Prowincja Odry. Subregion środkowej Odry południowy. . In: Hydrogeologia regionalna Polski. Wody słodkie. PIG, Warszawa

Thonipara A, Runst P, Ochsner C, Bizer K (2019) Energy efficiency of residential buildings in the European Union – An exploratory analysis of cross-country consumption patterns. Energy Policy 129:1156–1167. https://doi.org/10.1016/J.ENPOL.2019.03.003

Tokarczyk TSW (2020) Susze w Polsce– czy to normalne?? Obserwator Gzazeta obserwatora IMGW

Van Loon AF (2015) Hydrological drought explained. Wiley Interdisciplinary Reviews: Water 2:359–392. https://doi.org/10.1002/WAT2.1085

Wiśniowski Z (2007) Region dolnej Odry i Zalewu Szczecińskiego. In: Hydrogeologia regionalna Polski: Wody słodkie. . PIG, Warszawa

370 Zhao Z, Lin YF, Stumpf A, Wang X (2022) Assessing impacts of groundwater on geothermal heat exchangers: A review of methodology and modeling. Renew Energy 190:121–147. https://doi.org/10.1016/J.RENENE.2022.03.089

(2018) Studium uwarunkowań i kierunków zagospodarowania przestrzennego gminy Międzyzdroje. Międzyzdroje