Spatial distribution and hydrochemistry of springs and seepage springs in the Lubuska Upland of western Poland

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ABSTRACT

The major part of the Polish Plain (central Europe) was shaped during the last glaciation and so far has been considered to be poor in groundwater outflows. The present study aimed to map the groundwater outflows and to analyse their water properties in the Lubuska Upland, western Polish Plain. The mapping of the groundwater outflows was supplemented by hydrochemical analyses (major ions and trace metals) of selected outflows. Altogether, approximately 600 groundwater outflows were recorded, of which 45% were springs. The outflow water discharges ranged from 0.001 to 45 L s^{-1}. Most of them were located at the bottom of the slopes of river valleys. The water was neutral (pH 6.9 to 8.11), with electrical conductivity from 261 to 652 μS cm^{-1} and average temperature ~10 °C. The most common water type was dominated by bicarbonate, sulphates and calcium ions. The waters often exceeded the quality limits for total Fe and Mn^{2+}. This study revealed that groundwater outflows are a common feature of the areas shaped by former glaciations and are most likely supplied by shallow aquifers.

Key words | groundwater outflows, hydrochemistry, Lubuska Upland, Poland, seepage springs, springs

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INTRODUCTION

The natural emergence of groundwater on the land surface is called a groundwater outflow or simply – a spring. Outflows have been classified in various ways (see e.g., Steinmann 1915; Thienemann 1922; Alfaro & Wallace 1994; Springer & Stevens 2009). They may be divided, for instance, depending on the outflow type into springs characterised by concentrated water outflow or seepage springs with diffuse water outflow (Kresic 2010). Groundwater outflows are good indicators of the hydrological cycle (e.g., Alfaro & Wallace 1994; Manga 2001; Alley *et al.* 2002; Kresic & Stevanovic 2010). The properties of emerging groundwater can provide information about groundwater environment conditions and processes and input to river waters. Changes in the properties of these waters may reflect various processes in the groundwater environment, the impact of climate change and anthropogenic activities. Moreover, the relatively easy access of groundwater outflows water makes their analysis a useful way of monitoring the groundwater environment. The importance of the knowledge of the chemical status of such a groundwater system is also related to requirement of EU Water Framework Directive to establish control systems and sustain the quality of water bodies, including groundwater systems by 2015. Thus, many studies have investigated spring waters to gain insight into the properties, chemical status and quality of groundwater (e.g., Rademacher *et al.* 2001; Mendoza *et al.* 2006; Al-Khashman 2007). Isotopic studies of spring waters have also been used to interpret groundwater circulation patterns (El-Naser & Subah 2000; Larsen *et al.* 2001; Vandenschrick *et al.* 2002; Zuber *et al.* 2004; Günay 2006; Uliana *et al.* 2007). Moreover, measuring groundwater outflow discharges is a good indicator of the water budget in a particular area (Birk *et al.* 2004).

Groundwater outflow (spring) types differ in a number of ways (see Kresic 2010) including often linked hydrological and hydrochemical characteristics. According to the

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dominant type of groundwater outflow and host rock type, the outflows are frequently divided into either layered outflows if the water drains from unconsolidated sediments or fissure or fault springs if the water flows from rock fissures and karst springs (also called tabular or cave springs). The water properties of these various spring types differ and depend on the recharge area, interactions with the host rocks and the water circulation speed. For instance, water mineralization (i.e. the dissolved ion content) is usually much higher in karst areas than in other areas composed of crystalline rocks. It is mainly because the karst rock porosity enables water to flow slowly at contact with minerals that are able to dissolve easily (calcite dissolution is much faster than silicate weathering). Moreover, an important difference between fissured/karst springs and groundwater outflows from porous sediments is the discharge variability, i.e., the reactivity to seasonal or punctual infiltration modifications (e.g., Alfaro & Wallace 1994: Kløve *et al.* 2011).

Groundwater outflows in Poland are common in the southern regions (mountains), but they are considered to be rare in the north within the Polish Plain, which was shaped by the Pleistocene glaciations. In a recent review, Chełmicki *et al.* (2011) pointed out the scarcity of observations and data on groundwater outflows in the Polish Plain, in particular in its western part. In other parts of the Polish Plain, the situation is similar, except some areas of central (Moniewski 2004; Puk 2005), north-western (Mazurek 2006, 2008) and north-eastern (Jekatierynczuk-Rudczyk 1999) Poland, where understanding of groundwater outflows has significantly increased due to investigations conducted mostly during the last decade.

The objective of the present paper is to present the first regional groundwater outflow mapping, description and hydrochemical analyses from the Lubuska Upland, which is a major part of the western Polish Plain, and to assess the potential role of the outflows in terms of groundwater quality assessment.

STUDY AREA

The study area encompasses most of the Lubuska Upland, located in western Poland (Figure 1), with an area of approximately 5,200 km^2. The geomorphology is mainly the result of the last glaciation, and the most common landforms are sandur plains with a number of kettle holes, remnants of sub-glacial tunnel valleys, and morainic plateaus composed mostly of glacial tills. The highest elevation of 227 m a.s.l. is found within a ridge of push moraine. The area is dominated by Quaternary deposits of variable thickness, from a few metres to more than 150 m near the Gryżynka River. The average thickness of the Quaternary deposits is 83 m (Choiński 1981), and they are composed mainly of Pleistocene sediments with minor amounts of Holocene sediments. The Pleistocene sediments are of glacial and glaciofluvial origin, and are mainly composed of intercalated sands, gravels, glacial tills, muds and varved clays. Figure 2 provides an example of a geological cross section through the study area. The shallowest groundwater level is closely related to local geology and surface morphology; it is 1 m below the land surface in the river valleys and tunnel valleys, up to 2.5 m below the land surface in the nearby land depressions, 2 to 5 m below the surface of the sandur plains and up to 20 m below the surfaces of the uplands (Paczyński 1995). The Lubuska Upland is drained by 12 small rivers that are characterised by relatively stable discharge throughout the year (Choiński 1981). Moreover, the area is characterised by numerous lakes. Most of the area is covered by forests (51%) and agriculture land (40.7%). The remaining land belongs to urban areas (villages and towns: 5.1%) and unused land and water bodies (3.2%) (Central Statistical Office 2012). Most of the groundwater outflows are in forested areas (Figure 1). The climate is transitional between temperate oceanic and continental. The temperatures are among the highest in Poland, and the annual average is 8 °C. The annual average precipitation is approximately 600 mm, with slightly more precipitation occurring during the summer season.

METHODS

Mapping of groundwater outflows

The field mapping was preceded by analyses of the existing hydrological, hydrogeological and topographical maps. The map analyses were followed by interviews with representatives of the local administration, forest workers, protected

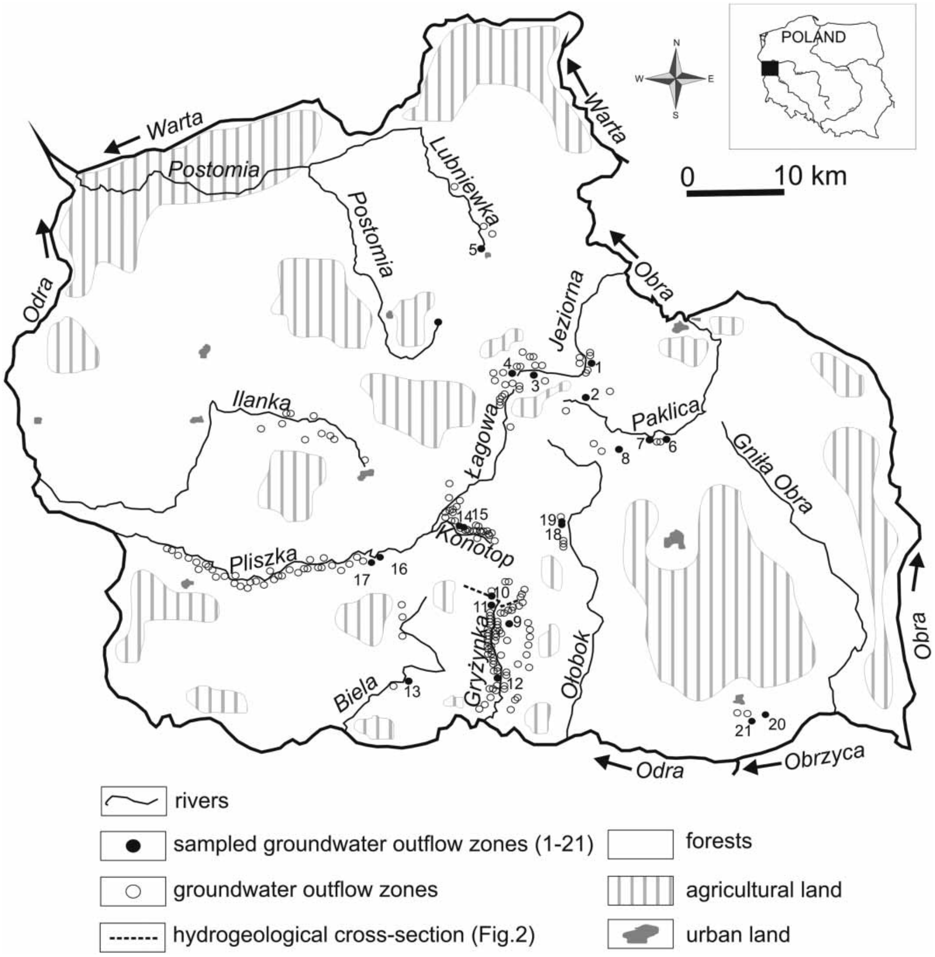

Figure 1 | Study area. The inset map shows the location of Lubuska Upland in Poland. The main map presents the main river systems, land use types and mapped groundwater outflows. Springs sampled for water hydrochemistry analyses are numbered.

area workers and local residents to collect new accounts on the groundwater outflows in the studied region. Finally, based on previous experiences in detailed spring mapping in part of the present study area – Gryżynka River valley (Szczucińska 2009) – areas of the highest probability of groundwater outflows were selected for detail field mapping. These areas included primary river valleys, tunnel valleys formed by sub-glacial drainage during the last glaciation and the margins of the uplands. The mapping was conducted from March 2011 to April 2013. For each groundwater outflow were noted: the geographical coordinates (using a global positioning system (GPS) by Garmin), the geomorphological situation (under hillside, hillside, valley, stream channel), the type of groundwater outflow (spring or seepage spring, descending or ascending), number of springs and seepage springs in groundwater outflow zone (GOZ), groundwater discharge assessment and land use nearby GOZ.

The descending and ascending water flow direction was confirmed on the basis of multiple visits of the springs used for the hydrochemical analyses and was defined according to Kresic (2010) as emerging under unconfined conditions where water table intersects land surface (descending), and discharged under pressure due to confined conditions in the underlying aquifer (ascending). The latter were characterised by evident upward flow underlined by bubbling and elevated water surface.

The water discharge in bigger outflows was measured in two ways. The first, so-called volumetric method, was based on collecting total water discharge in buckets of known

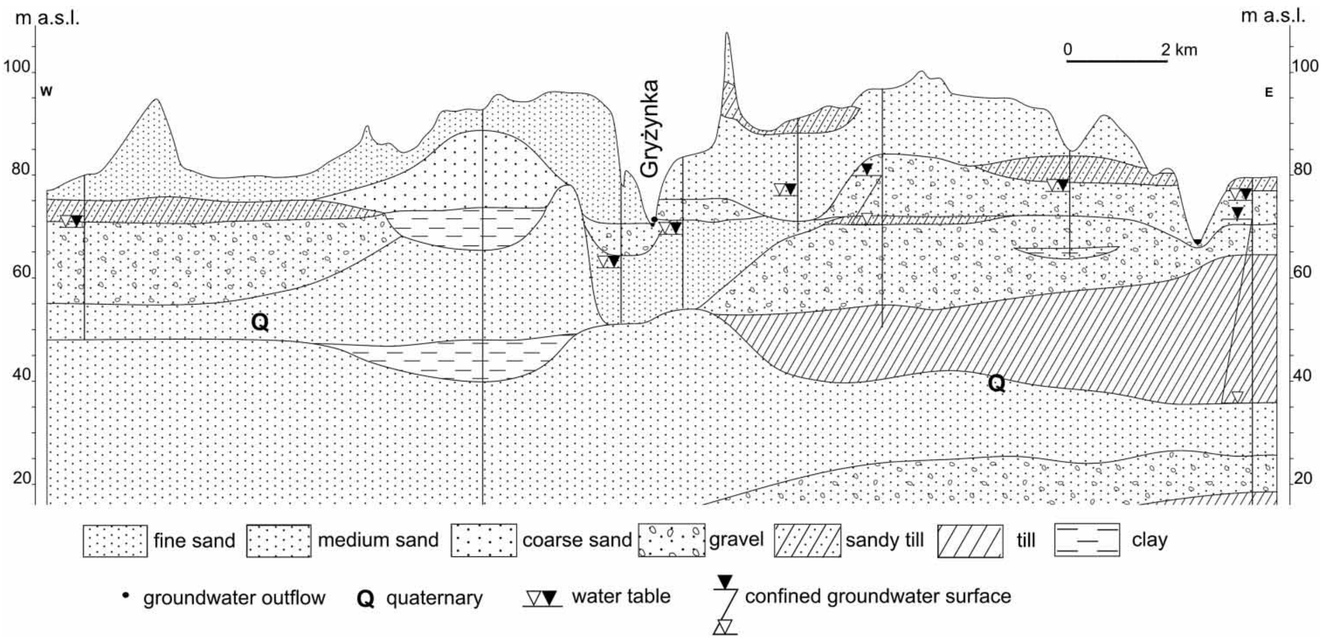

Figure 2 | Hydrogeological cross section through Quaternary deposits in Gryżynka catchment, southern Lubuska Upland. See Figure 1 for cross section location.

volume and measuring the duration of the water collection. The discharge was then calculated from ratio of sampled water volume to sampling duration. The second, hydrometric method was applied for GOZs drained by a single stream. In such cases, the water discharge measurements were made just from the GOZs in the streams using a hydrometric meter and standard calculation methods. In the remaining outflows, the discharge was assessed by visual comparison (mostly for seepage springs with very little discharge).

The water temperature, electrical conductivity (EC) and pH were measured for each outflow. The temperature was measured with the electrical thermometer ETI 2001, with an accuracy of 0.1 °C. Electrical conductivity was measured with conductivity meter CC-401 by Elmetron, with automatic compensation to a reference temperature of 25 °C and accuracy ±0.1%. The pH was measured with the handheld pH meter 315i by WTW, with an accuracy of 0.01 pH units.

Water sampling

Among the mapped groundwater outflows, 21 springs (Figure 1) representing various spring types, water discharges and electrical conductivities were selected for more detailed hydrochemical analyses. The water samples were collected on 4–5 November 2011 in polypropylene bottles. The subsamples for the major cation and metal analyses were treated with nitric acid. Subsamples for the iron analyses were collected in glass bottles. At the same time, the groundwater outflow water temperature, EC and pH were measured as described above.

Hydrochemical analyses

The hydrochemical analyses were conducted in a certified Laboratory of Environmental Research 'Aquanet' in Poznań following Polish and international norms PN-EN ISO 9963–1:2001, 17294–2:2006 and 10304–1:2009, PN-ISO 6059:1999, 6332:2001 and 7150–1:2002, PN-EN 1484:1999, 26777:1999 and 27888:1999. The analyses were conducted using the following methods:

- High performance fluid chromatography (for SO_4^{2-}, Cl^-, PO_4^{3-} and NO_3^-).
- Inductively coupled plasma mass spectrometry (ICP-MS) (for Na^+, K^+, Ca^{2+}, Mg^{2+}, Zn^{2+}, Pb^{2+}, Cd^{2+}, Cu^{2+}, Cr^{3+} and SiO_2).
- Spectrophotometry (for Fe, NO_2^- and NH_4^+).
- Atomic absorption spectrometry (AAS) (for Mn^{2+}).
- Titration (for HCO_3^- and hardness).

The ionic (charge) balance error expressed as the difference between cation and anion charges divided by their sum and multiplied by 100% did not exceed 5%.

Data analysis

The data on physical and chemical water properties were analysed using AquaChem 3.7 for water types and the Piper diagram. Statistical analyses (cluster analyses) were conducted using STATISTICA 10.

RESULTS

Eleven river catchments on the Lubuska Upland were mapped for the groundwater outflows. Their characteristics are listed in Table 1. During the mapping, 207 GOZs were documented. A single GOZ may contain several closely spaced springs and/or seepage springs. A total of 303 springs and 368 seepage springs were identified. In 62% of cases, the outflows were located at the foot of a slope (under hillside outflows); 18% of the outflows were located on slopes (hillside outflows), 12% in river valley floors (valley outflows) and 8% in river channels above the stream water surface (stream channel outflows). The stream channel outflows may be submerged during very high stream discharges and the valley outflows may be submerged only during very big floods. Among the GOZs, 92% were characterised by descending water flow, 2.5% were characterised by ascending water flow and 5.5% were of mixed type (in some of the GOZs, the groundwater emerges in both descending and ascending way).

Twenty-one of the studied GOZs were used for detailed hydrochemical analyses (Figure 1 and Table 2). The median values and ranges of the analysed properties for all the GOZs are presented in Table 3. The studied waters were 10.9 °C on average and neutral (pH 7.5), with an average EC of 428 μS cm^{-1}. Most of the major ion concentrations were similar in most of the outflows. According to hydrochemical classification, 86% of the groundwater outflow water belonged to $Ca\text{-}HCO_3\text{-}SO_4$ type, and the remaining to $Ca\text{-}HCO_3$ type (Figure 3). The concentrations of most of the analysed metals were low, except for total Fe and Mn^{2+}; the concentrations of these elements were relatively high and reached 14 mg L^{-1} and 1.5 mg L^{-1}, respectively.

DISCUSSION

Occurrence of groundwater outflows

The presented results from the Lubuska Upland show that in the studied region, but likely also in the remaining part of the Polish Lowland, which is characterised by similar morphology and geological history, groundwater outflows are a common feature. In particular, they are common in river valleys and tunnel valleys. The spring density index, defined as the number of groundwater outflows per 1 km^2, is variable within the studied area. For the river catchments, the spring density index varied between 0.02 and 0.95 springs per 1 km^2. The upper index values are near the range of values that are typical for mountainous areas, e.g., in granitoid parts of the Tatra Mountains (Chełmicki *et al.* 2011). The variable index values are mainly caused by the geomorphology of the area. In particular, the presence of the deep erosional incisions is important for the common presence of the outflows. Most of the outflows, specifically those with the highest water discharges, were documented in the catchments of the Gryżynka, Konotop, Łagowa and Pliszka Rivers. These rivers partly follow deep glaciogenic tunnel valleys, which have been incised into thick glaciofluvial sands and silty sands with hydraulic conductivity values in the range of 2×10^{-6} to 9×10^{-5} [m s^{-1}] (Szczucińska 2009), locally intercalated by thin tills. These sediments serve as regional groundwater aquifers. The tunnel valleys are up to 90 m deep as in the case of the Łagowa River valley, and their slopes are relatively steep (locally >30°) so probably also the groundwater level is also inclined and along with voluminous aquifers and porous sediments may partly explain high groundwater discharges from springs.

Properties of groundwater outflows waters

The obtained hydrochemical data were analysed along with the existing hydrological, hydrogeological and geological data. The analyses focused on problems of spatial variability

Table 1 | Basic characteristics of the mapped groundwater outflows in the studied river catchments in Lubuska Upland

			Outflow types					**GOZ position**			
Region (river catchment)	**Catchment area (km^2)**	**No. groundwater outflow zones (GOZs)**	**Springs**[a]	**Seepage springs**[a]	**Descending**	**Ascending**	**Descending and ascending**	**Under hillside**	**Hillside**	**Valley**	**Stream channel**
Gryżynka River	74	70	152	192	58	5	7	50	5	9	6
Pliszka River	389	45	74	43	43	1	1	29	11		5
Konotop River	47	22	25	26	22			3	13	4	2
Jeziorna River	120	20	12	21	20			10	4	5	1
Ilanka River	495	10	8	16	10			1	3	4	2
Łagowa River	61	10	11	6	10			10			
Paklica River	278	10	9	30	7		3	8		1	1
Ołobok River	56	7		13	7			6		1	
Biela River	288	5	10	13	5			3		2	
Lubniewka River	132	4	1	4	4			4			
Radowice protected area	–	4	2	2	4			3	1		

[a] Most GOZs consist of a number of springs or seepage springs.

Outflow types describe if the groundwater outflow is concentrated (spring) or diffuse (seepage spring), and if the water flow is downward gravity driven (descending), upward (ascending), or a mixture of descending and ascending. Outflow position describes the location of the outflow in regard to morphological features: at the slope bottom (under hillside), on the slope (hillside), on the valley floor (valley) or adjacent to a river channel (near stream channel).

Table 2 | Characteristics of the 21 selected groundwater outflow zones (GOZs) sampled for hydrochemical analyses. See Figure 1 for the GOZ locations and caption of Table 1 for explanations of outflow type and position

River catchment	GOZ no. (as on map – Figure 1)	No. of springs	No. of seepage springs	Outflow type	Outflow position	Water discharge (L s^{-1})	Thickness of vadose zone (m)	Land use nearby the GOZ
Paklica	2	1	4	Desc-asc	Under hillside	3	2	Agriculture area, village
Paklica	8	–	1	Desc	Under hillside	0.4	<10	Forest, village, agriculture area
Paklica	7	1	2	Desc	Under hillside	1	<10	Forest, agriculture area
Paklica	6	1	–	Desc-asc	Under hillside	0.7	<10	Forest, agriculture area
Biela	13	10	3	Desc	Under hillside	6	2	Forest
Konotop	14	4	–	Desc	Hillside	1	<10	Forest
Konotop	15	1	–	Desc	Hillside	0.2	<10	Forest
Ołobok	19	–	1	Desc	Under hillside	0.2	<10	Forest, agriculture area
Ołobok	18	–	4	Desc	Under hillside	0.3	<10	Forest, agriculture area
Lubniewka	5	1	1	Desc	Under hillside	0.5	<10	Forest
Jeziorna	3	1	–	Desc	Under hillside	0.7	2	Forest
Jeziorna	1	1	1	Desc	Under hillside	0.4	5	Forest, village
Jeziorna	4	2	–	Desc	Under hillside	0.5	<5	Forest
Radowice	21	1	–	Desc	Under hillside	0.15	5	Forest
Radowice	20	1	1	Desc	Hillside	3	5	Forest
Pliszka	16	–	2	Desc	Hillside	0.2	5	Forest
Pliszka	17	5	–	Desc	Under hillside	4	5	Forest
Gryżynka	9	2	–	Desc-asc	Under hillside	3	<10	Forest, tourist area
Gryżynka	10	4	6	Desc	Under hillside	5	<10	Forest, village, agriculture area
Gryżynka	11	7	5	Desc-asc	Under hillside	20	<10	Forest, agriculture area
Gryżynka	12	1	–	Desc	Under hillside	0.6	5	Forest

of groundwater outflow water hydrochemistry, groundwater supply (shallow vs. deep circulation) and potential dependence on local geology. To facilitate the data analyses all the data, after standardisation, were analysed using cluster analyses (Figure 4). The results were compared to regional information extracted from geological and hydrogeological maps and cross sections (rock/sediment types, regional directions of groundwater flow, the thickness of vadose zone) and own observations on groundwater outflow type and discharge.

The dominating hydrochemical water type reflects groundwater of the Quaternary sediment aquifers in the region, which are also dominated by Ca-HCO_3-SO_4 type. Probably, the formation of the studied waters is typical for the Polish Plain evolution model of precipitation waters changing during infiltration into shallow groundwaters (Macioszczyk & Dobrzyński 2007). According to the model, the groundwater is mainly supplied by low mineralisation ($EC = 20\ \mu S\ cm^{-1}$) precipitation (rain, snow) water dominated by ions of Ca^{2+}, Mg^{2+}, Na^{+}, SO_4^{2-} and Cl^{-}. This water infiltrates through, on average, a 2 to 10 m thickness of vadose zone, and is subjected to hydrochemical changes caused by weathering of aluminosilicates, redox changes of sulphur and nitrogen compounds, mineralization of organic matter, sorption and ion exchange. As a result of those processes, groundwater is enriched in ions of Ca^{2+}, Mg^{2+}, K^{+}, HCO_3^{-}, SO_4^{2-}, as well as total Fe and Mn^{2+} compounds.

Table 3 | Selected statistical characteristics of the analysed parameters in the groundwater outflows waters (for the 21 outflows)

Parameter	Units	Maximum	Minimum	Median	Mean	Standard deviation	European Council Directive	Polish upper limits for the groundwater class III ('satisfactory quality')
Ca^{2+}	mg L^{-1}	110	44	76	77	20		200
Cd^{2+}	mg L^{-1}	0.0005	0.00001	0.00001	0.002	0.002	0.005	0.005
Cl^{-}	mg L^{-1}	22.7	3.02	11.6	10.6	5.2	250	250
Cr^{3+}	mg L^{-1}	0.0012	0.0001	0.0002	0.0003	0.0003	0.05	0.05
Cu^{2+}	mg L^{-1}	0.0054	0.0002	0.0011	0.002	0.002	2	0.2
Electrical conductivity	μS cm^{-1}	652	261	437	436	109	2500	2,500
Hardness ($CaCO_3$)	mg L^{-1}	330	120	210	213	59		700
HCO_3^{-}	mg L^{-1}	384	79.3	183	190	66		500
K^{+}	mg L^{-1}	3.7	0.5	1.1	1.3	0.8		15
Mg^{2+}	mg L^{-1}	16	1.5	4.6	5.4	4.0		100
Mn^{2+}	mg L^{-1}	1.5	0.002	0.13	0.225	0.32	0.05	1
Na^{+}	mg L^{-1}	13	4.1	7	7.2	2.2	200	200
NH_4^{+}	mg L^{-1}	0.31	0	0.01	0.035	0.07	0.4	1.5
NO_2^{-}	mg L^{-1}	0.042	0.002	0.007	0.011	0.012	0.5	0.5
NO_3^{-}	mg L^{-1}	31	0	1.9	4.2	7.3	50	50
Pb^{2+}	mg L^{-1}	0.016	0.0001	0.0011	0.0029	0.004	0.01	0.1
pH		8.11	6.9	7.5	7.45	0.3		6.5–9.5
PO_4^{3-}	mg L^{-1}	0.42	0	0.12	0.14	0.13		1
SiO_2	mg L^{-1}	8.7	4.2	5.6	6.0	1.4		50
SO_4^{2-}	mg L^{-1}	116	12	60.4	56	22	250	250
Temperature	°C	15.4	8.5	10.5	10.9	1.7		16
Total Fe	mg L^{-1}	14	0.052	0.74	2.42	3.8	0.2	5
Zn^{2+}	mg L^{-1}	0.04	0.0004	0.0033	0.006	0.009		1

Council Directive (1998) on the quality of water intended for human consumption and Polish upper limits for the groundwater class III ('satisfactory quality') (Rozporządzenie Ministra Środowiska 2008) are provided for comparison.

The studied outflows are likely supplied from areas composed mainly of glaciofluvial sands and gravels. Moreover, in the probable recharge areas of some outflows, No. 2–11, 17, 20 and 21, are also glacial tills. The land use types nearby the groundwater outflows include forests, agricultural areas, villages and mixtures of them. However, the difference in the land use and sediment types nearby the particular groundwater outflows are not reflected in the cluster analyses based on hydrochemical data, which showed that all the outflows are very similar (Figure 4). Some of the outflows revealed even greater similarity and were clustered into small groups, which appear to be related to particular sites, for instance, the outflows in the river valleys of Gryżynka (No. 9–12), Konotop (14 and 15), Ołobok (18 and 19), Paklica (2, 6 and 7) and in Radowice protected area (20 and 21). The overall hydrochemical similarity of the outflow is in line with the documented water types, which follow the typical regional model of shallow groundwater evolution (see the previous paragraph). Small spatial variability may suggest that all of the outflows are supplied from shallow groundwaters recharged probably from similar glacifluvial sandy aquifers. However, in the northern part of the study area, there are common glacitectonic deformations, which may enhance the supply of groundwater from deeper geological structures. However, such a possibility is not supported by the presented data, and it would

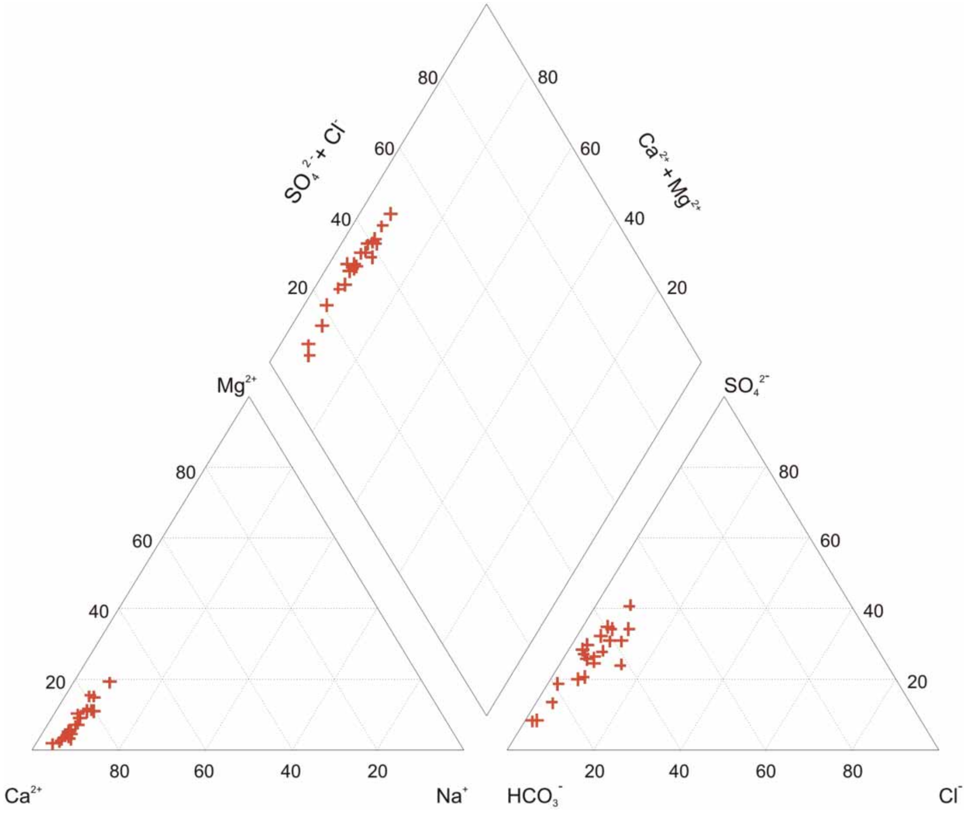

Figure 3 | Piper diagram showing hydrochemistry of the studied spring waters.

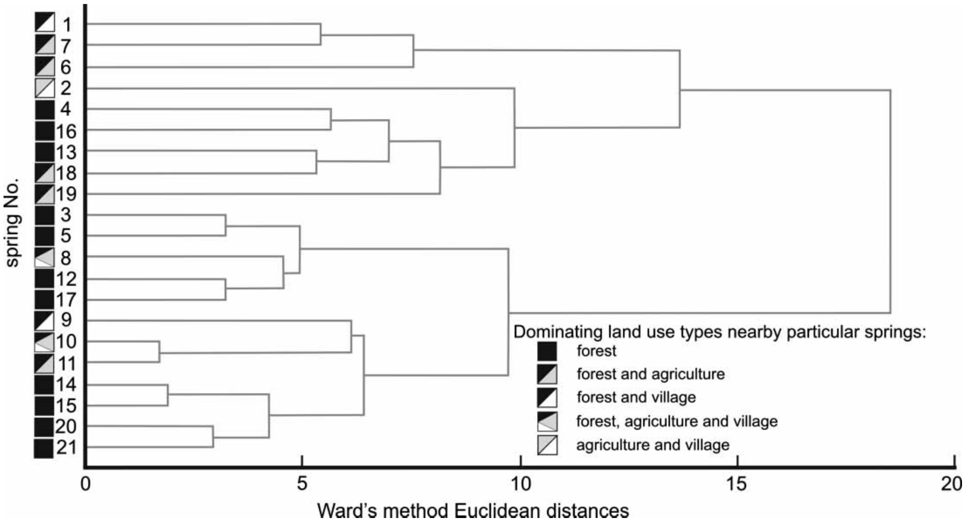

Figure 4 | Results of cluster analyses of spring water hydrochemistry for all the analysed elements and compounds. A small Ward's distance means that the water chemistry is similar. The dominating land use types nearby particular springs are also marked.

need to be confirmed with isotopic methods to assess the age of the groundwater.

The mapped groundwater outflows are characterised by a wide range of water discharges – from less than 0.01 $L\,s^{-1}$ to over 40 $L\,s^{-1}$ in some springs in the Gryzynka River valley. The outflows with the largest water discharges are usually situated at the bottom of the slopes. However, several outflows with discharge of 5 $L\,s^{-1}$ (Pliszka River valley) and even 15 $L\,s^{-1}$ (Ilanka River valley) were also found on slopes. The outflows' discharge may depend on many parameters including section of springs, local hydraulic conductivity, local hydraulic gradients, size of aquifer among others. The difference in the documented hydrochemical properties are not significant between the springs of various discharges. The similarity in water chemistry despite differences in discharge rate may suggest that weathering materials are abundant (i.e., not depleted anywhere) and weathering kinetics probably do not limit export of dissolved constituents. Mazurek (2008), in her study on hydrochemistry of groundwater outflow waters supplied from the shallowest aquifer and those supplied from deeper Quaternary aquifers in NW Poland, also found no significant differences. However, understanding of water supply routes for particular springs requires further studies including the combination of hydrological, hydrogeological, hydrochemical, isotopic and modelling methods.

Although the overall hydrochemical properties of the studied waters were very similar and ion concentrations low, some of the analysed elements were in excess of national (Rozporządzenie Ministra Środowiska 2008) and international drinking water limits (WHO 2004). The Polish national regulations classify groundwaters into five classes. Classes I, II and III refer to very good, good and satisfactory quality, respectively. Waters in those classes are considered to be affected by human activity to a very small degree. The upper limits of concentrations for particular elements and compounds are included for class III in Table 3. Classes IV and V refer to unsatisfactory and poor quality and are considered to be affected by anthropogenic activity. In most of the studied groundwater outflows, water quality is classified as class I and II (Rozporządzenie Ministra Środowiska 2008) and is within the limits of drinking water according to WHO (2004) and Council Directive (1998). However, with regard to concentrations of total Fe and Mn^{2+}, some of the outflow waters were contaminated. The concentrations of total Fe were found to be in the range of 0.052 to 14 $mg\,L^{-1}$. The total Fe limit permitted for drinking water according to WHO (2004) and Council Directive (1998) is 0.2 $mg\,L^{-1}$. This means that in most cases (81%) in the groundwater outflow waters the concentrations of total Fe are in excess of the limits. The highest concentrations were found in springs in the Gryżynka River (No. 10 and 11) and nearby lake Niesłysz (No. 19). In the case of Mn^{2+}, the WHO (2004) and Council Directive (1998) limits for drinking water are 0.05 $mg\,L^{-1}$, and in 76% of the studied outflows the documented concentrations were higher (up to 1.5 $mg\,L^{-1}$ in spring No. 19). The higher contents of those metals were previously noted by Szczucińska *et al*. (2010) in several springs in the Gryżynka River catchment and it was found that their concentrations may change seasonally, probably due to natural, temperature- and pH-controlled reactions of shallow groundwater with aquifer sediments. Although the higher concentrations of total Fe and Mn^{2+} are not very harmful for humans, they cause the water to have a characteristic 'metallic' taste and are often a reason for stains and changes in the colour of clothing during washing.

Nitrates were not detected ($NO_3^- < 0.1\,mg\,L^{-1}$) in some of the studied springs, however, in some of them they reached up to 31 $mg\,L^{-1}$. The natural hydrogeochemical background values for groundwater in Poland are, according to Witczak & Adamczyk (1995), less than 1 $mg\,L^{-1}$. The highest concentrations of nitrates (with concentrations $>1\,mg\,L^{-1}$) were found in the northeast part of the study area, which is dominated by agriculture, and is likely the main reason for the local contamination of groundwater with nitrates. High concentrations of nitrates (up to 72 $mg\,L^{-1}$) were also found in shallow groundwater in Quaternary deposits of western Poland by Dragon (2013). The concentrations of NO_3^- exceeding 50 $mg\,L^{-1}$ are considered to be hazardous for human health, in particular for children and older people.

CONCLUSIONS

The conducted studies in the Lubuska Upland show that groundwater outflows are common in lowland regions shaped by the Pleistocene glaciations and have so far been underestimated in analyses of hydrological systems of these areas. They are most common in river valleys following old tunnel valleys. In a single GOZ, various types of outflows may be present: springs and seepage springs, with various discharges. The physical and hydrochemical properties of the groundwater outflow waters are similar in the study area, which is partly related to the common type of dominating Quaternary deposits serving as aquifers drain by the outflows. The hydrochemistry is dominated by ions of Ca^{2+}, HCO_3^-, SO_4^{2-} and water quality is relatively good except for high concentrations of total Fe, Mn^{2+} and NO_3^-.

Actions need to be taken in the case of plans to use the water for drinking (reduction of total Fe and Mn^{2+} concentrations); however, it can be used for agriculture and most industrial purposes.

Future studies are needed in order to specify the routeing of the groundwater and, in particular, the origin of the contaminants and possible seasonal variability.

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