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Hydrographic and hydrochemical characteristics of selected groundwater outflows in desert and semi-desert areas

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Abstract: The presence of natural groundwater outflows depends on many factors, such as lithology, geological structure, and climate. Areas with particularly poor crenological recognition are arid and semi-arid regions, primarily due to rarity of groundwater outflows in these locations. The article presents the hydrographic and hydrochemical characteristics of selected groundwater outflows in arid and semi-arid areas. In addition to hydrographic mapping, basic physical parameters of water were measured in selected springs, such as temperature (*T*, °C), electrolytic conductivity (*EC*, $\mu S \cdot cm^{-1}$), and reaction (pH, –). Laboratory analyses determined the major cations and anions in water: Ca^{2+}, Mg^{2+}, Na^+, K^+, NH_4^+, SO_4^{2-}, Cl^-, NO_3^-, Br^-, PO_4^{3-}. The analyses were performed using an ion chromatograph Metrohm 850 Professional IC. Twenty-four natural groundwater outflows in South America, Africa, and Asia were selected for research. It was found that the vast majority of outflows are transit sources. Their supply area may be far from discharge points. The supply source is rainwater or meltwater from high mountain massifs. Other types of outflow are springs of alluvial fans and braided rivers. They are fed by waters from glacial rivers, which infiltrate alluvial deposits and flow back to the surface. Hydrochemical analysis has shown that the physicochemical properties of water in dry areas vary significantly. Still in the hydrochemical type, there is a predominance of sulphate, chloride, and sodium ions. This distinguishes the spring waters from these areas in temperate latitudes, which are dominated by bicarbonate and calcium ions.

Keywords: desert, groundwater, hydrochemical type, hydrochemistry, spring

INTRODUCTION

The presence of natural groundwater discharges depends on many factors such as lithology, geology, and climate (Taloor *et al.*, 2020; Stevens, Schenk and Springer, 2021). While Stevens Schenk and Springer (2021) suggest that there are at least 2.5 mln springs in the world, research shows that the total number is much larger and will likely remain unknown. According to Bhat and Pandit (2020), there are over 5 mln springs in India alone. Despite the importance of springs for regional biodiversity (Cantonati *et al.*, 2012) and as a vital source of drinking water in some regions, the study of these natural water outflows has attracted only little interest, reflected in the scientific literature. The number of publications on springs is small comparing to other hydrographic features, such as rivers or lakes. As Kresic and Stevanovic (eds.) (2009) and Springer and Stevens (2009) suggest, not all global hydrological sources are entirely classified.

Areas with particularly poor crenological recognition are arid and semi-arid areas. Therefore, research was undertaken in these areas with the aim of:

- classification of outflows according to their type, including spring, spring flush, effusion, etc.;
- classification according to the type of aquifer, i.e. fracture, rubble, karst, etc.;
- classification according to geomorphological location, namely valley, trough, and slope;
- determination of outflow supply areas;
- determination of the composition and hydrochemical type of water;
- determination of hydrological and hydrochemical similarities or differences between the tested outflows.

MATERIALS AND METHODS

LOCATION OF THE STUDIED OBJECTS

Groundwater outflows in deserts and semi-deserts of South America, Asia, and Africa were selected for research (Fig. 1). Table 1 presents the detailed location of the tested outflows and their basic hydrological characteristics.

RESEARCH METHODS

The study of natural groundwater outflows was carried out following the methodology of Gutry-Korycka and Werner-Więckowska (eds.) (1996). Field mapping was preceded by a chamber study of Soviet military maps at the scale of 1:50,000 and 1:100,000 and other topographic maps, such as those published by Kompass (1:50,000; map sheet Tenerife and

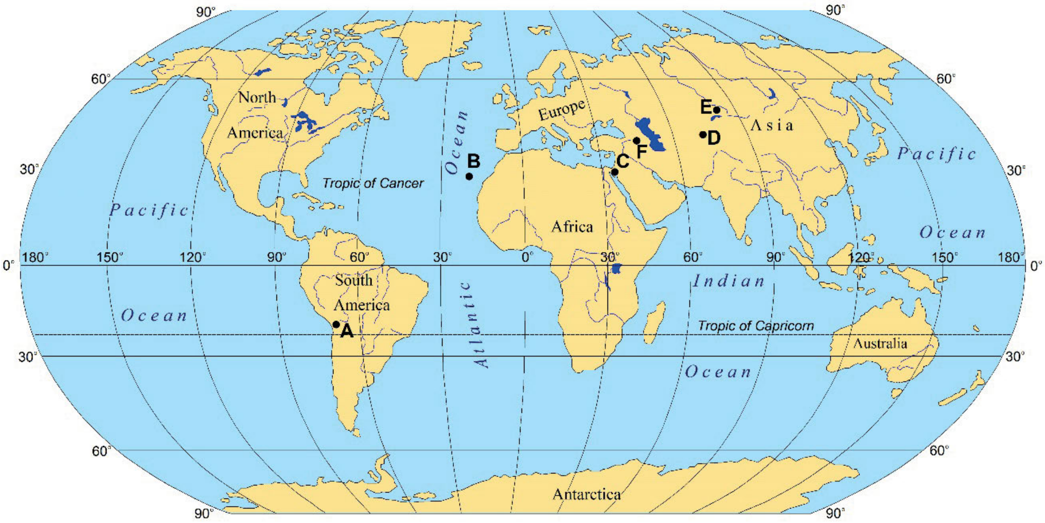

Fig. 1. Location of the studied springs; A = Andy (springs: 1–4 and 23), B = Canary Islands (springs: 20–22), C = Jordan (springs: 5–9), D = Tien-szan (springs: 17–18), E = Altynemel (spring – 19), F = Caucasus mountains (springs: 10–16 and 24); source: own elaboration

Table 1. Location and basic parameters of the studied outflows

No.	Name	UTM	Elevation (m a.s.l.)	Type of water outflow	Climate zone acc. to Kőppen–Geiger	Geomorphological location	Lithology
1	Guaneguare	18°09'51.0"S 69°16'20.0"W	4,640	fens	BWk	slope	volcanic rocks
2	Huasco	20°15'44.8"S 68°52'33.6"W	3,790	source	BWk	edge	volcanic rocks
3	Parajaya	19°07'15.3"S 68°54'34.7"W	4,240	source	BWk	valley	volcanic rocks
4	Puchultisa	19°24'25.9"S 68°57'28.7"W	4,200	source	BWk	valley	volcanic rocks
5	Dana	30°40'44.8"N 35°36'50.4"E	1,300	karst spring	BWk	slope	limestone
6	Afra I	30°58'01.8"N 35°38'35.2"E	300	source	BWk	valley	sandstone
7	Afra II	30°58'04.1"N 35°38'29.3"E	290	source	BWk	valley	sandstone
8	Main	31°36'30.5"N 35°36'50.6"E	–264	source	BWk	valley	limestone
9	Lawrence	29°33'34.3"N 35°24'36.7"E	1,040	source	BWh	slope	sandstone
10	Bozdag	40°40'38.0"N 46°53'34.1"E	120	source	BSk	slope	sandstone (gypsum inserts, salt)
11	Dassjus I	41°10'09.0"N 46°55'56.8"E	395	source	BSk	slope	sands, gravels (alluvial formations)
12	Dassjus II	41°02'00.4"N 47°10'23.7"E	350	source	BWk	slope	sandstone/conglomerate
13	Angels I	39°56'44.9"N 44°44'40.7"E	1,010	source	BWk	valley	sandstone
14	Angels II	39°56'29.4"N 44°44'32.9"E	1,020	source	BSk	valley	sandstone
15	Shaki	39°33'58.0"N 46°00'04.5"E	1,700	source	BSk	valley	volcanic formations
16	Lusashogh	39°50'18.4"N 44°58'01.3"E	1,920	source	BSk	slope	sandstone
17	Komirshi	43°02'52.1"N 79°41'12.3"E	1,900	source	BSk	alluvial fan	sands, gravels (alluvial formations)
18	Chekildek	42°11'56.4"N 75°36'10.9"E	1,850	source	BWk	valley	sands, gravels (alluvial formations)

cont. Tab. 1

No.	Name	UTM	Elevation (m a.s.l.)	Type of water outflow	Climate zone acc. to Kőppen–Geiger	Geomorphological location	Lithology
19	Kalinino	44°10'03.2"N 78°45'31.3"E	1,000	source	BSk	alluvial fan	sands, gravels (alluvial formations)
20	Chafaris	29°07'23.2"N 13°30'30.3"W	350	source	BWh	valley	volcanic rocks
21	Tababaire	28°35'35.8"N 13°56'35.7"W	425	source	BWh	slope	volcanic rocks
22	Molinos	28°32'12.1"N 14°02'40.8"W	100	source	BWh	hillside	volcanic rocks
23	Churignaya	18°20'37.2"S 69°10'31.7"W	4,460	source	BWk	valley	volcanic rocks
24	Dassjus III	41°10'45.6"N 46°56'20.7"E	360	source	BWk	valley	sandstone/conglomerate

Explanations: B = arid (main climate), W = desert (precipitation), S = steppe (precipitation), h = hot arid (temperature), k = cold arid (temperature).
Source: own elaboration.

Fuerteventura (Kompass, 2018; Kompass, 2019)), where water outflows are marked using symbols. In addition, potential outflows were identified using Google Earth Pro satellite images. A green phototone (oases) easily identifies groundwater outflow zones in deserts. Potential outflow zones were verified during field hydrographic mapping. It should be mentioned that the green phototone also appears around artesian wells, and such areas were excluded from the study. Due to the extensive research area, field mapping was carried out between 2018 and 2023.

In addition to hydrographic mapping, basic physical parameters of water were measured in selected springs, such as temperature (*T*, °C), electrolytic conductivity (*EC*, $\mu S \cdot cm^{-1}$), and reaction (pH, –). Water samples were also taken for laboratory analyses. They were collected in polyethylene bottles of 100 cm^3 and transported in refrigerated conditions at 5 ±3°C. Before analyses, the samples were filtered through a nitrocellulose membrane with a pore diameter of 0.45 μm (GVS North America, USA).

Laboratory analyses included the determination of the major cations and anions in the water: Ca^{2+}, Mg^{2+}, Na^+, K^+, NH_4^+, SO_4^{2-}, Cl^-, NO_3^-, Br^-, PO_4^{3-}. The analyses were performed on an ion chromatograph Metrohm 850 Professional IC (anion column A Suup 7-250/4.0, eluent 3.6 mM Na_2CO_3 and a cation column C4-150/4, eluent 0.7 mM dipicolinic acid and 1.7 HNO_3). Bicarbonates (HCO_3^-) were determined in the field using titration with the alkalinity indicator b-r (blue–red). The analysis error in all tested samples was <3%, and in the vast majority of samples, it ranged from 0.8 to 1.5%.

The hydrochemical water type was based on the Altowski–Szwiec classification (Macioszczyk, 1987). This classification approach assumes that the hydrochemical type is determined based on the presence of ions whose content in water is greater than 20 ±3% mval in relation to the sum of anions and cations. The name of the water sample begins with the ion with the highest concentration, regardless of whether it is a cation or anion. Under natural conditions, the content of six essential ions exceeds 20% mval: Ca^{2+}, Mg^{2+}, Na^+, HCO_3^-, Cl^-, SO_4^{2-}.

The parameters characterising waters were subjected to principal component analysis (PCA) to examine the contribution of each variable in variation and to show relationships between them. Before this analysis, the parameters were scaled. Classifying groundwater outflows of under-cluster analysis (CA) was performed using Euclidean distance and Ward method as a grouping. The PCA and CA were done using R language and environment (R Core Team, 2022) and packages: “ade4” as well as “factoextra”.

RESULTS AND DISCUSSION

HYDROGRAPHIC CHARACTERISTICS

Permanent groundwater outflows in deserts are related to water transit from areas with higher water supply. An example of this type is outflow No. 1. It is associated with the orographic barrier of the volcanic cone. It is common knowledge that an increase in altitude (orographic barrier) forces condensation and, thus, an increase in precipitation. Even in the tropical zone, the tops of volcanoes may be covered with patches of eternal snow or glaciers. Examples of such objects are the volcanoes in the Andes on the border of Chile and Bolivia. Although the areas at their base are undoubtedly deserts, their tops are covered with snowfields. This is due to the very large denivelation between the top and the base of a volcano, which, as in the case of the Sajama volcano, exceeds 2,200 m. During ablation, the amount of melting water is sufficient for permanent or periodic water outflows on the slopes in the semi-arid zone. Outflows are most often associated with deep erosional cuts covering the slopes of volcanoes, an example of which is the tested outflow No. 1. Infiltration water circulates within the cuts in loose, weathered, alluvial material. Most often, the outflows are not concentrated. These are non-concentrated outflows (flushes) covered with characteristic hydrophilic vegetation, mainly moss (Photo 1, Tab. 1). On lower volcanoes (devoid of snowfields), rainwater may also be sufficient to produce outflows on their slopes. Outflows are not only related to erosional forms on the slopes.

In specific situations, e.g. a basin surrounded by several glaciated volcanoes, the amount of water may be so large that it

Photo 1. Unconcentrated groundwater outflows in the volcano’s erosion trough (Guaneguare, No. 1) (phot.: *T. Molenda*)

flows out at the bottom of the basin. An example is the basin located in the Sajama National Park, surrounded by Quisi, Parinacota, Pomerape and Sajama volcanoes. Outflows frequently have the character of spring fields, with several to a dozen or so concentrated outflows. Immediately below the outflow zone, a river network with an anastomosing (braided) channel type is formed. After the concentration of a more significant number of tributaries, the riverbeds change into winding or meandering. The length of rivers varies and, depending on the springs' efficiency, ranges from a few to several kilometres. Most rivers end their course within endorheic depressions (saltpans).

The second type of orographic barriers are mountain ridges. As in the case of volcanic cones, their upper parts may be covered with patches of eternal snow or glaciers. They also receive more precipitation, especially their slopes exposed to the inflow of wetter air masses (Kalesnik, 1973). Depending on the geological structure, water transfer from the mountains to their foreland may occur over long distances (Dawydow, Dmitrijewa and Konkina, 1979). In the case of Kalinino Springs (Kazakhstan, No. 20), the discharge zone is approximately 20 km from the main mountain ridge. Distances are not always so large, as evidenced by the Rum Massif in Jordan. As mentioned above, most springs flow out some distance from the mountain barrier. In this case, water transit is almost vertical. Water from the surface with greater supply infiltrates the rock massif, which is built mainly of sandstones of the Ramm group, and after reaching the impermeable layer of crystalline rocks (granites), flows out at the foot of the massif (Fig. 2). Outflows occur on its eastern part, related to the inclination of the granite layer. It is a typical example of a layer-contact spring. There are several springs of this type within the Rum Massif, some of which are permanent, such as the Lowrenc spring (No. 9). In the past, they were a vital source of drinking water for caravans travelling along this route.

Another specific type of a spring is related to alluvial fans. The flow of rivers into the foreground of mountains causes a sharp reduction in their slope and flowing water velocity. In the case of rivers heavily loaded with rock debris, this leads to the deposition of rock debris in extensive alluvial fans (Mycielska-Dowgiałło, Korotaj-Kokoszczyńska and Rutkowski, 2001). A characteristic feature of alluvial fans is the graining of fractions from coarser to finer within the longitudinal profile. This feature means that river waters, which easily infiltrate coarse-grained (usually gravel) sediments in the proximal part of the fan, encounter sediments of increasingly finer fractions as they move down the fan. In the distal part, there is a zone of intersection of groundwater with the topographic surface, which leads to water outflow (Fig. 3). These are barrier-type springs. They can also be classified as secondary water sources. This term was introduced, among others, by Tomaszewski (1996) for water that returned under the ground from the surface and then resurfaced. An example of this feature is the alluvial fan of the Komirshi River (No. 18) in south-eastern Kazakhstan (Fig. 4). Over 100 springs form a line of approximately 9 km. In addition to concentrated outflows, flush swamps are covered with specific hydrophilic vegetation. The efficiency of individual outflows varies, ranging from 0.1 to 3.0 $dm^3 \cdot s^{-1}$. In most cases, there are several gravitational (descending) outflows within one spring niche. The outflow line runs along a contour of 1,900 m a.s.l., and the spring supply area includes the high-mountain massif of Kietmień, the highest parts of which exceed 3,400 m a.s.l. (Molenda, 2018). According to oral information from a forester from Komirshi, the springs are permanent. Weathered material was found in spring niches.

An even more spectacular example of this type of outflow is the alluvial fan of the Tente River located in eastern Kazakhstan. It is 20 km long and 30 km wide at its base. The springs flow along a semicircular line related to the alluvial fan. The number of springs is significant, and the efficiency of the largest reaches several $dm^3 \cdot s^{-1}$. The springs are supplied by the infiltration of the Tente River waters into the alluvial fan sediments. Infiltration is supported by a dense network of channels and drainage ditches distributing water over the fan surface for agricultural purposes. Below the line of springs, water is also released in an unconcentrated form, contributing to the formation of vast wetlands. Depressions in the area accumulate water, leading to the formation of lakes. The outflow of water within the alluvial fans promotes the creation of unique spring-marsh-lake ecosys-

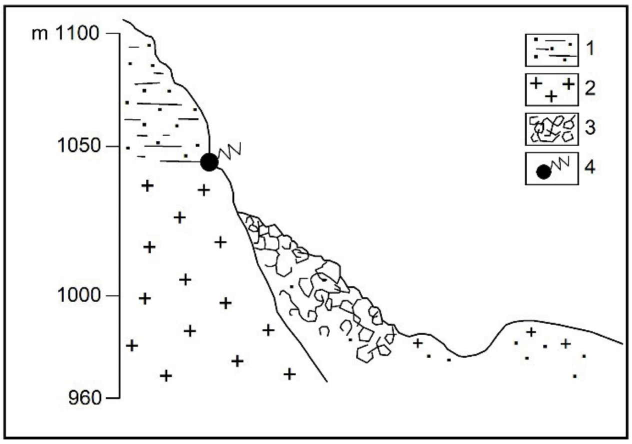

Fig. 2. Layer-contact springs in Wadi Rum: *1* = sandstone, *2* = granite, *3* = rubble stone, *4* = springs; source: own study

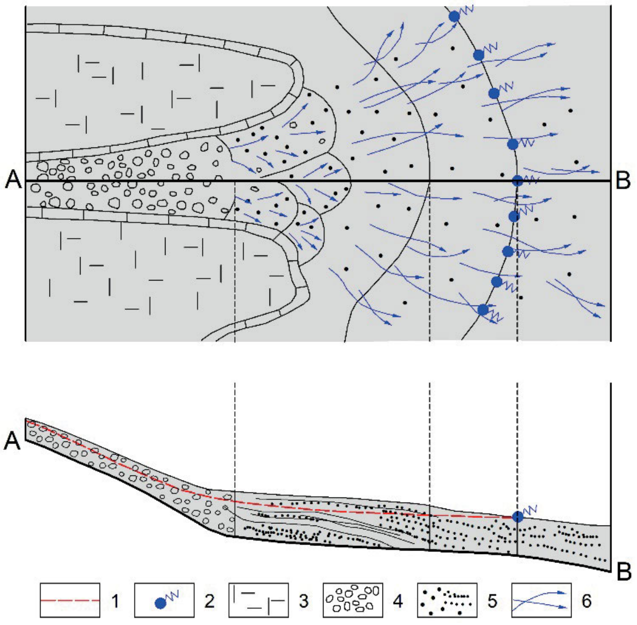

Fig. 3. Springs within the inflow cone; *1* = groundwater table, *2* = alluvial deposits, *3* = solid rocks, *4* = gravels and pebbles, *5* = sands, *6* = groundwater flow; source: own study

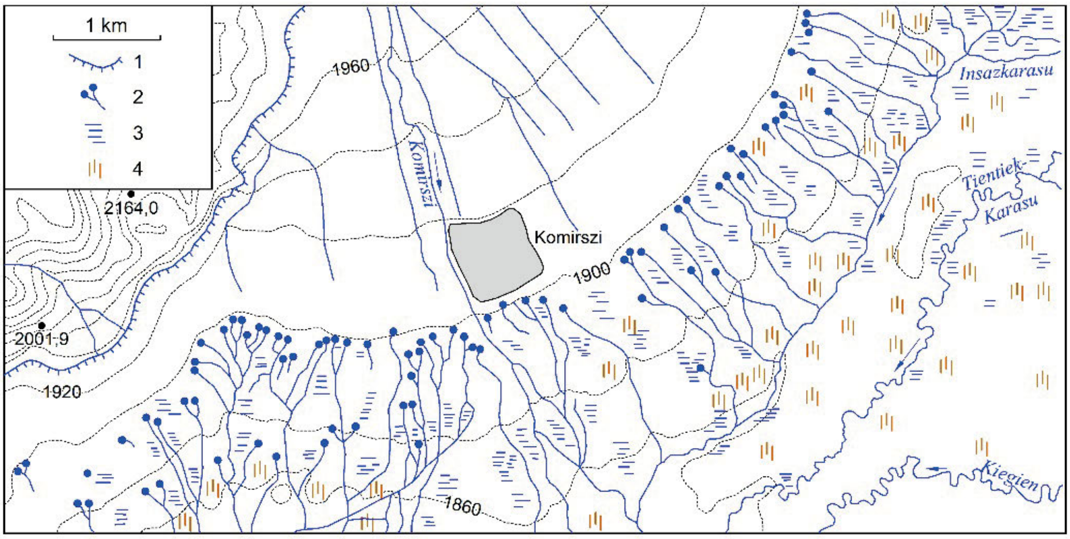

Fig. 4. Springs of the Komirshi inflow cone; *1* = canal, *2* = springs, *3* = wetland, *4* = salt marsh; source: own study

tems. Initially, these ecosystems are freshwater environments, which over time, due to water evaporation, gradually transition into saltwater systems.

A particular variety of such springs includes those within the braided parts of river channels. Glacial rivers flowing into the foreland of mountains or mid-mountain valleys (due to a sharp reduction in slope and overload with debris) may create a braided type of bed. River water may escape into the alluvial material within extensive beds of braided rivers. After underground (intra-alluvial) flow, these waters flow back to the surface as springs. An example of this type of spring may be the one related to the Kahchor River (No. 19). The mountain basin, in the vast alluvial riverbed, includes a complex of efficient springs (Fig. 5).

The springs described above are permanent, and their water supply is always related to the transit from areas with greater water supply. Typical desert springs are found in the Canary Islands such as Fuerteventura and Lanzarote. Despite annual precipitation on the islands being less than 150 mm, periodic outflows still occur, primarily in winter when rainfall is the highest. These springs are related to volcanic rocks and exhibit a fissured flow pattern. An example is the seepage zone in the Barranco de Los Molinos valley (No. 22). This zone is well identified by hydrophilic vegetation that grows over the linear layer-contact outflow (Photo 2). Layer-contact outflows at the basalt and tuff contact are also known from other volcanic areas, such as Georgia (Molenda, 2019). It should be emphasised that most springs on the islands are strongly anthropogenically modified. The change is two-faceted. First of all, rainwater infiltration is supported to increase the efficiency of springs. It is achieved by building stone and soil dykes that slow down surface runoff and force infiltration (Mioduszewski, 2007). This type is characteristic for desert areas. The niches themselves are also transformed. Most often, in the outflow zone, pools are carved out, which both retain water and make it more accessible.

Springs in semi-arid areas play a significant economic role. They are an essential source of water supply and thus a location factor for villages and cities. A spectacular example of this is Shaki in southern Armenia (No. 17). The efficiency of the spring

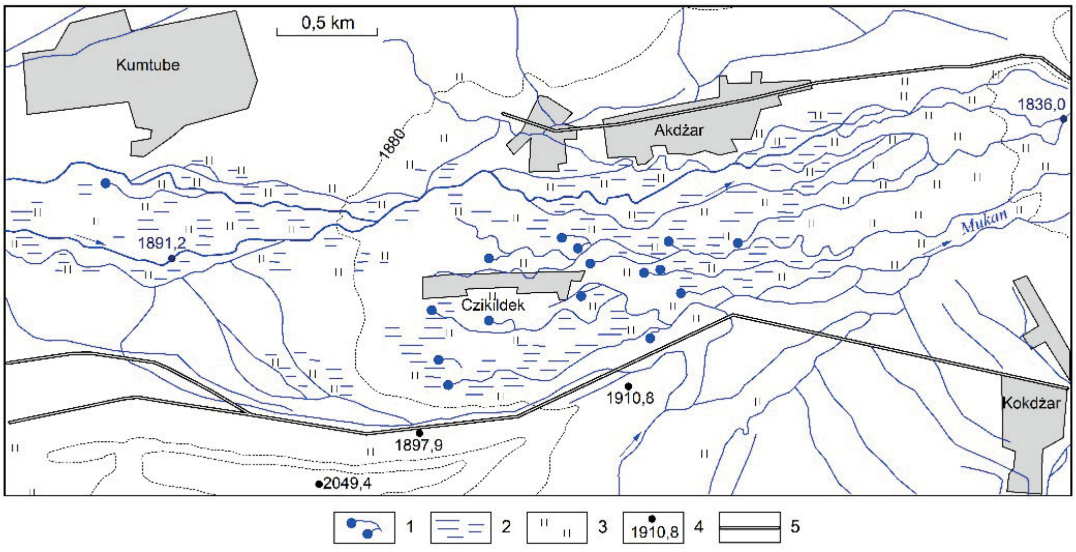

Fig. 5. Alluvial springs of the rift river; *1* = springs, *2* = wetland, *3* = fields, *4* = height about see level, *5* = roads; source: own study

Photo 2. Linear outflow of groundwater (Molinos, No. 22) (phot.: *T. Molenda*)

exceeds 1 $m^3 \cdot s^{-1}$. Therefore, there is an intake directly at the outflow to supply the town of Sisjan with approximately 14,000 inhabitants. A few hundred meters below the spring, another water intake is located. The water is directed through an underground adit to the hydroelectric power plant. Despite two large intakes, the remaining water is sufficient to create the impressive Shaki waterfall on the river. It is also important to mention that this spring already played an essential role in prehistoric times. A complex of megalithic buildings – Zorats Karer – is located close to the spring.

It should also be noted that anthropogenic groundwater outflows in the form of numerous artesian wells are a characteristic feature in semi-arid areas. They play a crucial role in the local agricultural economy. It applies in particular to Western Asia within the borders of former USSR republics.

HYDROCHEMICAL CHARACTERISTICS

The main factor shaping the physicochemical properties of groundwater is the geological structure with the lithology of rocks (Macioszczyk, 1987; Żelazny, 2012; Jasik, Małek and Krakowian, 2020; Molenda and Frydecka, 2021). Although many factors influence the chemical composition of water, there is a certain regularity related to the geographical location. In the case of hydrographic objects in the semi-arid zone, an increase in the concentration of sulphate ions (SO_4^{2-}) is observed, and in the arid zone, an increase in the concentration of chloride (Cl^-) and sodium (Na^{2+}) ions (Dawydow, Dmitrijewa and Konkina, 1979). The PCA showed that these ions play a significant role in explaining the variability between the tested waters (Fig. 6). The concentrations of sulphate (SO_4^{2-}), chloride (Cl^-), and sodium (Na^+) ions are correlated with the first axis of PCA accounting for 57.3%. The second axis, accounting for 25.8%, is associated with ammonium (NH_4^+) and fluoride (F^-) ions. They are identifiers of deep circulation groundwater associated with zones of tectonic faults or active volcanism. The same regularity was found in the case of the springs examined. Their water was often characterised by the di-ionic sulphate-sodium or chloride-sodium type (Tab. 2). The types found confirm the regularity in the formation of water chemistry.

However, in some cases, the lithological factor may ultimately determine the mineralisation and hydrochemical properties of water. Thus, the chemical composition of water

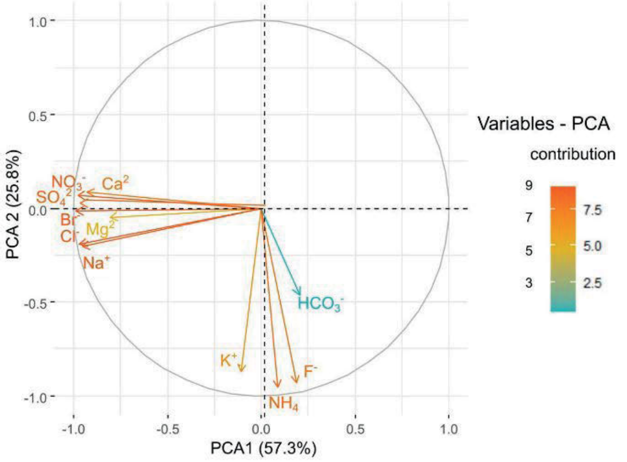

Fig. 6. The principal component analysis (PCA) diagram showing contribution and relationships among hydrochemical parameters of waters; source: own study

from such a source can be significantly different from other sources. An example is the group of springs in the Bozdag Massif (central Azerbaijan; No. 10). The multidimensional cluster analysis showed that the waters of this source were significantly different from the others (Fig. 7). Infiltration water feeding this spring circulates in Miocene rocks made of clay minerals with salt and gypsum inserts. The high solubility of these rocks means that the waters of the springs are highly mineralised (>20 $g \cdot dm^{-3}$) and rich with chloride-sulphate-calcium (Cl^--SO_4^{2-}-Ca^+). In the case of these springs, the temperature is also noteworthy: in July, it can reach 38°C. It is a consequence of shallow water circulation and, thus, a significant heat inflow from ground surface. The considerable impact of the water circulation depth on the temperature of spring waters has been documented in numerous studies (Pleczyński, 1985; Błachowicz, Buczyński and Staśko, 2019).

It should be mentioned that the waters of springs in areas with active volcanism are also very often warm or even hot (Bortnikova, Bessonova and Zelenskii, 2005; Bortnikova, Sharapov and Bessonova, 2007). In these cases, the heat flux of the rock bed is responsible for the high water temperature. Sources of this type were found, among others, within volcanic cones in the Andes on the border of Chile and Bolivia (Tab. 2). In hot outflow waters ($T > 50°C$), sodium (Na^+) always dominated among the cations and chlorides among the anions (Tab. 2). This hydrochemical type was also found in hot outflows associated with the fault zone of the Dead Sea basin (Main – No. 8, Tab. 2). In hot outflows, attention is also drawn to the high concentration of ammonia and bromides (Tab. 2). High concentrations of these anions were also found in the waters of the volcanic areas of Kamchatka (Bortnikova *et al.*, 2008).

Water enrichment with sodium chloride ions may also result from sea aerosol precipitation. The impact of sea aerosol precipitation on the chemical composition of water may reach several dozen kilometres from the coastline (Andrews *et al.*, 1999). It may be confirmed by the karst spring "Dana" (No. 5) located in the Dead Sea zone. Although the aquifer is made of limestone, it represents the bicarbonate-chloride-calcium (HCO_3^--Cl^--Ca^{2+}) hydrochemical type (Tab. 2). It is unusual because the waters of limestone karst outflows almost always

Table 2. Physicochemical properties of the waters of the studied outflows

Source name	No.	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	HCO_3^-	Cl^-	SO_4^{2-}	Br^-	F^-	NO_3^-	*EC* ($mS \cdot cm^{-1}$)	pH (–)	*T* (°C)	Hydrochemical type
		$mg \cdot dm^{-3}$														
Huasco	2	40.51	7.81	72.42	6.74	1.54	219.7	35.72	94.42	0.1	0.08	1.29	570	7.6	15.0	HCO_3^--Na^+
Puchultisa	4	18.79	1.88	1,653.54	217.04	29.31	231.9	3,237.99	160.16	6.1	4.27	6.65	8,390	7.9	80.0	Cl^--Na^+
Parajaya	3	130.04	61.17	113.97	20.43	1.95	115.9	143.94	760.25	0.3	0.66	1.17	1,555	7.1	26.0	SO_4^{2-}-Ca^{2+}
Chirihuaya	23	36.17	31.74	942.74	32.11	18.85	1,012.9	566.52	702.14	1.5	2.51	4.89	4,420	7.1	55.0	Na^+-Cl^--HCO_3^-
Guaneguare	1	9.10	2.00	1.60	1.30	0.00	20	3.50	8.20	0.0	0.00	8.00	48	6.4	9.0	Ca^{2+}-HCO_3^-
Dana	5	125.28	30.16	26.68	1.06	0.00	241	139.09	54.83	2.5	0.18	27.92	1,015	7.3	16.4	Ca^{2+}-HCO_3^--Cl^-
Afra I	6	50.21	19.20	36.15	2.00	0.06	155.6	57.53	59.78	0.2	0.24	0.13	610	7.2	44.0	HCO_3^--Ca^{2+}
Main	8	169.13	36.49	486.37	53.97	1.52	266.9	807.94	223.17	3.0	0.57	2.28	3,300	6.3	55.0	Cl^--Na^+
Lowrance	9	35.00	4.00	14.00	1.90	0.08	70	29.00	13.00	0.1	0.20	11.00	290	7.9	12.0	Ca^{2+}-HCO_3^-
Tababaire	21	15.40	12.94	305.77	7.42	0.00	213.6	385.42	57.20	1.3	0.20	21.85	1,700	8.3	13.0	Cl^--Na^+
Molinos	22	197.94	444.42	5,426.51	95.12	0.00	289.8	8,399.66	2,402.67	27.5	0.40	71.04	13,350	8.5	14.0	Cl^--Na^+
Chafaris	20	25.73	51.28	274.17	5.41	0.00	271.5	419.31	114.24	1.4	0.30	10.78	1,750	8.7	14.0	Cl^--Na^+
Dassjus I	11	254.96	88.93	106.27	3.01	0.00	335.61	44.54	840.07	0.8	0.76	12.85	1,970	7.5	19.0	SO_4^{2-}-HCO_3^--Ca^{2+}
Dassjus II	12	132.53	11.03	244.64	3.89	0.00	137.3	119.47	627.04	1.0	0.54	25.15	1,602	8.1	19.2	SO_4^{2-}-HCO_3^--Na^+
Dassjus III	24	158.95	8.76	8.76	1.75	0.00	149.5	87.73	696.52	0.6	0.50	25.81	1,933	7.7	20.0	SO_4^{2-}-HCO_3^--Na^+
Bozdag	10	2,654.00	303.69	7,209.00	8.34	0.00	106.78	12,639.00	13,369.95	99.3	0.00	212.39	37,700	7.5	31.0	Cl^--Na^+
Angels I	13	13.30	74.82	302.26	25.21	2.24	762.8	104.68	349.60	1.0	1.98	5.52	3,440	6.5	25.0	HCO_3^--Na^+
Angels II	14	25.75	65.33	125.71	7.11	0.08	353.9	69.50	229.89	0.5	1.16	2.80	2,050	6.3	27.0	HCO_3^--SO_4^{2-}-Na^+-Mg^{2+}
Shaki	15	74.56	13.41	9.67	3.54	0.00	280.69	8.08	16.39	0.0	1.01	7.64	161	7.1	9.2	HCO_3^--Ca^{2+}

Explanations: *EC* = electrochemical conductivity, *T* = temperature.
Source: own study.

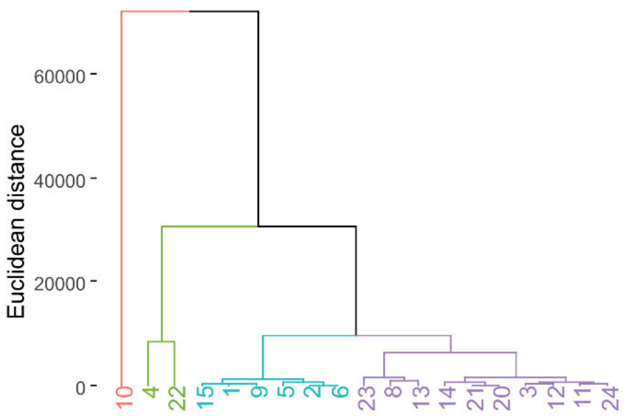

Fig. 7. The multidimensional clustering of springs due the chemical composition of their water; source: own study

belong the di-ionic bicarbonate-calcium (HCO_3^--Ca^{2+}) hydrochemical type (Żelazny *et al.*, 2007; Żelazny, 2012; Siwek, 2013a; Siwek, 2013b; Molenda and Frydecka, 2021). The impact of marine aerosol precipitation is also evident in the case of sources in the Canary Islands. In the case of the Molinos spring (No. 22), the exceptionally high concentration of chlorides and sodium made it similar to the Puchultis spring (No. 4) from the volcanic area (Fig. 7).

Outflows in semi-arid areas are not always characterised by increased mineralisation and the dominance of chloride-sulphate-sodium ions. Examples are outflows of flush springs in erosion channels on the slopes of Andean volcanoes covered with snowfields (Photo 1). Meltwaters move quickly and at a small depth within the rubble material that fills erosion channels. This translates into the very low mineralisation of water ($EC < 50$ $\mu S \cdot cm^{-1}$) and the water is categorised as a two-ion bicarbonate-calcium hydrochemical type (HCO_3^--Ca^{2+}) (Guaneguare – No. 1, Tab. 2).

CONCLUSIONS

Despite unfavourable climatic conditions, arid and semi-arid areas have natural groundwater outflows. Permanent outflows are always related to water flow (transit) from areas with greater water supply. Fault zones may play an essential role in this transit. Other authors also point out to the critical role fault zones play in supplying springs. Most often, in Central Asia (Tian-Shan massif) and South America (Andes), the alimentation areas are mountain chains, very frequently glaciated, which become an efficient water source during the melting period. Springs in desert areas may also be supplied with water from glacial rivers. These are frequently sources of alluvial fans or braided rivers. They can be classified as secondary sources. This term was introduced, among others, by Tomaszewski to denote water that returned from the surface to the ground and resurfaced again. In other areas, outflows are periodic or episodic and occur during rainfall (e.g. Fuerteventura, Lanzarote). In such cases, outflows are not related to groundwater reservoirs but only to the flow of rainwater through the rock mass.

In arid areas, the physicochemical properties of water vary. The findings of the multidimensional cluster analysis showed that the sources that differ significantly from the rest were related to a specific type of rocks (e.g. salt rocks). This confirms that the rock type shaped groundwater chemistry. The dominance of sulphate, chloride, and sodium ions was observed in the waters of the tested sources. This was reflected in the hydrochemical type of the tested waters, where chloride-sodium or sulphate-bicarbonate-sodium waters dominated. This distinguishes the waters of these areas from those of mid-latitude springs with a dominant bicarbonate-calcium hydrochemical type. The depth of water circulation determines the temperature of outflow waters. Outflows that are influenced by atmospheric factors have a lower temperature than those that are influenced by the heat of the bedrock.

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CONFLICT OF INTERESTS

The author declares no conflict of interests.

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