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Baltica

BALTICA Volume 33 Number 1 June 2020: 97–108
https://doi.org/10.5200/baltica.2020.1.9

Geohydraulic conditions and post-treatment at riverbank filtration sites in Eastern Europe

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Kruć, R., Dragon, K., Górski, J., Nagy-Kovács, Z., Grischek, T. 2020. Geohydraulic conditions and post-treatment at riverbank filtration sites in Eastern Europe. *Baltica*, *33 (1)*, 97–108. Vilnius. ISSN 0067-3064.
Manuscript submitted 5 November 2019 / Accepted 25 May 2020 / Published online 25 June 2020

Abstract. Managed aquifer recharge is gaining in importance worldwide. As there is not much information on bank filtration (BF) sites in Eastern Europe, a survey of geohydraulic conditions and post-treatment schemes carried out. Such information will make it possible to assess hydraulic conditions in the region and the commonly required post-treatment. Data were collected from publications, archival documentations, maps as well as through direct communication with administrators of relevant water companies. As a result, a summary of the data from 71 BF or BF/artificial recharge (AR) well fields in the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Russia, Serbia, Slovakia and Slovenia was prepared. Data on the source of water, location, capacity, aquifer thickness and hydraulic conductivity, and treatment methods were collected. Thirteen of the studied 71 RBF well fields are combined with AR. The most common type of BF in Eastern Europe is riverbank filtration (RBF) with wells located along a river. 56% of the analyzed sites are located along larger rivers such as the Danube, Drava, Nemunas, Neris, Odra, Volga, Warta and the Wisła. The smallest BF site has a discharge capacity of only 38 m^3/day, the largest BF site 210,000 m^3/day, while the smallest and the largest combined BF/AR site has a discharge capacity of 5,500 m^3/day and 150,000 m^3/day, respectively. The average values of aquifer thickness and hydraulic conductivity are 21 m and $2.7*10^{-3}$ m/s, respectively, at BF sites and 16 m and $5.7*10^{-4}$ m/s, respectively, at BF/AR sites. The most common post-treatment steps include aeration-filtration – disinfection, UV, ozone and activated carbon being used at many sites as well. The collected data can prove helpful in designing and modernizing BF sites, comparing and establishing direct contacts with water companies facing similar conditions. The outcome of this study is the built-up BF database for Eastern Europe, which can supplement the Global Inventory of Managed Aquifer Recharge Schemes (IGRAC 2017).

Keywords: *managed aquifer recharge; artificial recharge; survey; hydraulic conductivity; aquifer thickness; treatment methods*

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Abbreviations:
AR – artificial recharge
BF – bank filtration
HW – horizontal collector well
GAC– granulated activated carbon
MAR – managed aquifer recharge
NOM – natural organic matter
RBF – riverbank filtration
TOC – total organic carbon

INTRODUCTION

It was more than 100 years ago that for getting drinking water of better microbiological quality and taste, direct use of surface water was replaced by groundwater abstraction or bank filtration (BF). At present, the knowledge of surface water pollution with organic trace compounds acts as an additional driving force for moving away from direct abstraction of surface water. Furthermore, BF offers various advantages, including buffering capacity in cases of extreme events and pollutant spills (Grischek, Schoenheinz 2002; Grischek *et al*. 2002). Additionally, managed aquifer recharge (MAR) is an alternative to over-abstraction of groundwater and for handling droughts (Dillon *et al*. 2019). MAR includes BF and artificial recharge (AR). To meet increasing water demands, in Eastern Europe, BF schemes were combined with AR schemes for infiltration of pre-treated surface water. Meanwhile, in Asia and Africa, the ongoing activities are focused either on installation of new BF schemes (Freitas *et al*. 2012; Wahaab *et al*. 2019; Sandhu *et al*. 2019) or on recharge basins for AR.

The BF technique is based on abstraction wells located close to a river or lake (Fig. 1a), whereas that of AR (Fig. 1b) is based on abstraction of surface water and artificial infiltration via basins, ponds, trenches or wells. Both techniques can provide large quantities of water of improved quality as a result of its passage through the aquifer. Physical, biological and chemical processes such as mixing, dissolution/precipitation, sorption, redox processes and biodegradation occur in the aquifer (Hiscock, Grischek 2002). As a result, particles, biodegradable organic compounds, numerous organic micro pollutants, pathogens and nitrates are completely or partly attenuated (Dragon *et al*. 2018; Sharma, Amy 2009). Commonly, the abstracted water is a mixture of bank filtrate or basin infiltrate and groundwater.

Application of BF has been popular (especially in Europe) for many decades and has gained a higher interest in the 90ies in the US in a sense of removal credits for pathogens. The water supply system of Budapest, the capital city of Hungary, is completely based on bank filtration. Other large cities in Europe, such as Berlin, Bratislava, Poznań, Prague and Wrocław receive a major part of their drinking water from bank filtration. Hiscock, Grischek (2002) reported that 50% of drinking water in Slovakia comes from bank filtration, this figure for Hungary and Germany being 45% and 16% respectively. However, with time these numbers are slightly changing. It should be mentioned that many perspective well fields are based on BF. Comprehensive information on MAR sites in Europe can be found in the Global Inventory of Managed Aquifer Recharge Schemes (IGRAC 2017) (Fig. 2), Sprenger *et al*. (2017) and Dillon *et al*. (2019).

Compared to MAR schemes in Central and Western Europe, only limited information is available on operational BF and AR schemes in Eastern Europe. The article aims to provide more information about BF sites in Eastern Europe, their hydrogeological conditions and post-treatment and to fill a gap in the Global Inventory of Managed Aquifer Recharge Schemes (IGRAC 2017). The article summarizes the data research covering the following countries (in alphabetical order): Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Russia, Serbia, Slovakia and Slovenia. Thus, in this paper, we present the information on BF/AR in Eastern Europe. The data presented herein are expected to prove useful in designing new BF sites or modernizing the existing ones.

METHODOLOGY

The data collection from Eastern European countries is the result of the action taken to implement the EU AquaNES project "Demonstrating synergies in combined natural and engineered processes for water treatment systems". All material was collected in the period 2017–2019. The data were collected using the following approaches:

– direct contact via phone calls and email communication with administrators of the waterworks,

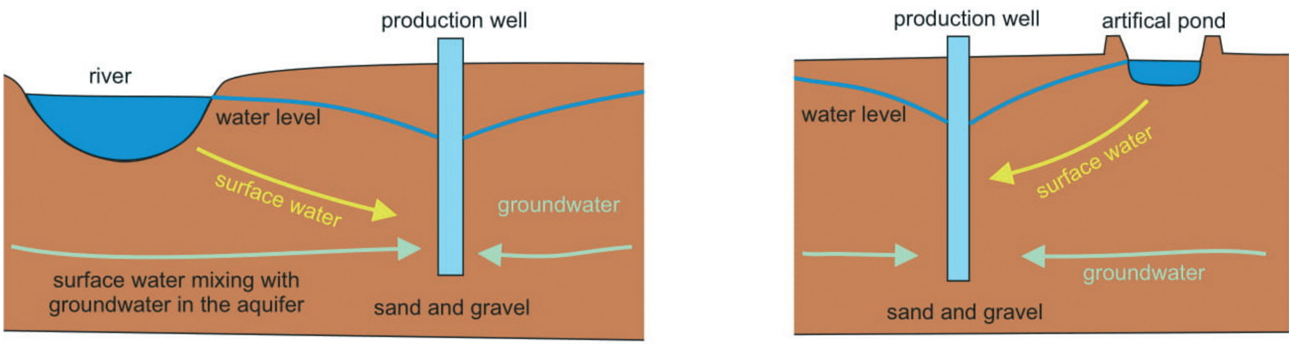

Fig. 1 Schemes of bank filtration (a) and combination of bank filtration and artificial recharge (b) (Hiscock, Grischek 2002, changed)

authorities and associations connected with water supply, hydrogeology and environmental protection (each site got the same survey),

– literature research (publications, archives, state websites, website facilities, materials from various types of studies, private companies) and survey of databases,

– search for well fields and waterworks along major rivers and lakes using maps, aerial photographs and Google Earth.

The data on 55% of well fields were collected from publications, conference papers, books, websites and other documents, the remaining data being obtained through direct contact.

The data set includes the country and city, where the well fields exist, the source of water, capacities, such aquifer data as hydraulic conductivity and thickness, and post treatment technology. Data are given in the form of average values or range. A comparison between the two types BF and BF/AR sites in terms of capacity, hydraulic conductivity and aquifer thickness was made. Median and average values were calculated, but, as a significant variability within the BF and BF/AR groups was found, the range of values is given as well. For comparison of data, average values were used. Additionally, the BF (Mosina-Krajkowo, Poland) and AR (Dębina, Poland) well fields are described in detail to explain conditions. For these two sites, the most detailed information was collected.

Although the data presented herein certainly do not cover all BF well fields in Eastern Europe (e.g., there are 49 BF sites in operation in Hungary, but only 19 were included in the presented database, because of data unavailability), they significantly supplement the existing IGRAC database (2017), which mainly covers Western Europe. The current survey has provided data on 48 BF sites that are not yet included in the IGRAC database. All the collected data could be included in the Global Inventory of MAR Schemes (IGRAC 2017).

RESULTS

In 11 countries of Eastern Europe, 71 bank filtration sites were identified (Fig. 3). Only 13 of the well fields were a combination of BF and AR. The most common type of BF in Eastern Europe is riverbank filtration (RBF) with wells located along a river, ditch or channel (Table 1). As many as 56% of all sites in Eastern Europe are located along larger rivers, such as the Danube, Drava, Nemunas, Neris, Volga, Warta and the Wisła.

Table 2 presents data on the country, city, water source and references. Each well field is assigned a different number.

Capacities of BF schemes show a wide variation (Fig. 4). Low- capacity BF well fields predominate in Poland, whereas in Hungary, on the contrary, high-

Fig. 2 Location of main type MAR in Europe according to IGRAC (2017)

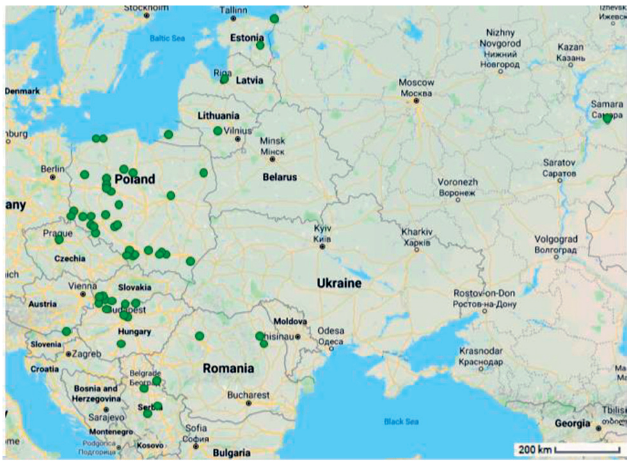

Fig. 3 Location of BF and BF/AR sites in Eastern Europe

Table 1 Number and type of BF sites in selected countries of Eastern Europe

Country	Czech Republic	Estonia	Hungary	Latvia	Lithuania	Poland	Romania	Russia	Serbia	Slovakia	Slovenia
Lake BF						1					
River BF		2	20	1	1	21	1	2	4	4	1
Combined BF/AR	1					10	2				

Table 2 List of BF well fields (w.f.) with an assigned number (waterworks no.), dc – direct contact

No.	Country	City	Water source	Reference
1	Czech Rep.	Karany	R. Izera	Grischek, Schoenheinz 2002
2	Estonia	Tartu	Meltsivesk spring	dc
3		Narva	R. Narva	dc
4	Hungary	Győr	R. Danube	dc
5		Esztergom	R. Danube	Grischek *et al*. 2002
6		Koppánymonostor	R. Danube	Grischek *et al*. 2002
7		Szob	R. Danube	www.vizugy.hu/index.php?module=vizstrat&programelemid=149
8		Baja	R. Danube	dc
9		Kisoroszi w.f.	R. Danube	dc
10		Tahitótfalu w.f.	R. Danube	dc
11		Kisoroszi w.f.	R. Danube	dc
12		Pócsmegyer w.f.	R. Danube	dc
13		Szigetmonostor, Horányi w.f.	R. Danube	dc
14		Szigetmonostor, Monostori w.f.	R. Danube	dc
15	Hungary	Szigetmonostor, Pócsmegyeri w.f.	R. Danube	dc
16		Szigetmonostor, Sziget I–II. w.f.	R. Danube	dc
17		Budapest, district 4	R. Danube	dc
18		Budapest, district 3	R. Danube	dc
19		Budapest, district 13	R. Danube	dc
20		Halászteleki w.f.	R. Danube	dc
21		Szigetújfalui w.f.	R. Danube	dc
22		Ráckeve I. w.f.	R. Danube	dc
23		Ráckeve II. w.f.	R. Danube	dc
24	Latvia	Baltezers, Riga	R. Daugava	Grischek *et al*. 2002
25	Lithuania	Kaunas	R. Nemunas and Neris	dc
26	Poland	Poznań–Dębina	R. Warta, artificial basins	Górski 2011; Górski *et al*. 1999; dc
27		Mosina–Krajkowo	R. Warta, artificial basins, oxbow lake, channel	Górski 2011; Górski *et al*. 1999; Górski, Przybyłek 1997; dc
28		Bydgoszcz	R. Brda, artificial basins	Dąbrowski *et al*. 2004; dc
29		Kalisz–Lis	R. Prosna	Kaczmarek 2017
30		Wrocław–Mokry Dwór	R. Oława	dc
31		Legnica–Przybków	R. Kaczawa artificial basins	Górski 2002; dc
32		Warszawa	R. Wisła	Górski 2002; dc
33		Bielsko Biała–Kobiernice	R. Sola	dc
34		Kraków–Bielany	R. Sanka and Wisła	Olko 2008; dc
35		Białystok–Wasilków	R. Supraśl	dc
36		Jelenia Góra–Grabarów	R. Bóbr	Marszałek *et al*. 2008; dc
37		Zgorzelec	R. Nysa	Pleczyński, Ryszkowska 1986, dc
38		Oborniki–Kowanówko	R. Wełna	dc
39		Kołobrzeg	R. Parsęta	kolobrzeg2000.home.pl; dc
40		Mostowo–Koszalin	Lake Rosnowskie	Pleczyński, Przybyłek 1974; Stemporowska 2004; dc
41		Śrem	R. Warta	Dragon *et al*. 2005
42		Gorzów Wlkp.–Siedlice	R. Warta	pwik.gorzow.pl; dc
43	Poland	Tarnów Świerczków	R. Dunajec	Haładus *et al*. 2011; Wojtal *et al*. 2009; dc
44		Kępa Bogumiłowicka	R. Dunajec	Haładus *et al*. 2012; dc
45		Zbylitowska Góra	R. Dunajec	Haładus *et al*. 2012; dc
46		Toruń–Jedwabno	R. Drwęca	wodociagi.torun.com.pl; dc
47		Oświęcim–Zasole	R. Soła	Byczyński *et al*. 1976; Cudakiewicz *et al*. 2005; pwik.oswiecim.pl
48		Pogórze Skoczów	R. Wisła and Brennica	dc
49		Kończyce–Rudnik	R. Wisła and Brennica	dc
50		Brzegi–Ustroń	R. Wisła	dc
51		Bogatynia	R. Miedzianka	dc
52		Przemyśl	R. San	Zdechlik, Karpińska 2009; dc
53		Karłów i Błażejowice–Kłodzko	R. Nysa Kłodzk, Bystrzyca Dusznicka	bip.powiat.klodzko.pl; dc
54		Krzyżowice–Brzeg	Artificial channel	brzeg24.pl; dc
55		Gierszowice–Brzeg	Local spring and artificial channel	dc
56		Marciszów Górny, Ptaszków	R. Bóbr	Krawczyk *et al*. 2003; dc
57		Marciszów Dolny	R. Bóbr	Krawczyk *et al*. 2003; dc
58	Romania	Floresti	R. Somesu Mic	dc
59		Gheraiesti I and Gheraiesti II–Bacau	R. Bistrita	Grischek *et al*. 2002
60		Timisesti	R. Moldavia	dc
61	Russia	Kaliningrad	R. Pregol	Grischek *et al*. 2002
62		Samara	R. Volga	dc
63	Serbia	Kraljevo	R. Ibar	Grischek *et al*. 2002
64		Belgrade	R. Sava and Danube	Ray *et al*. 2002
65		Brzan	R. Velka Morava	Petrovic, Zivanovic 2015
66		Kovin–Dubovac	R. Danube	Kovacević *et al*. 2017
67	Slovak Rep.	Gabčíkovo	R. Danube	Grischek *et al*. 2002
68	Slovak Rep.	Kalinkovo	R. Danube	Grischek *et al*. 2002
69		Rusovce	R. Danube	Ray *et al*. 2002; Grischek *et al*. 2002
70		Samorín	R. Danube	Grischek *et al*. 2002
71	Slovenia	Maribor	R. Drava	Grischek *et al*. 2002

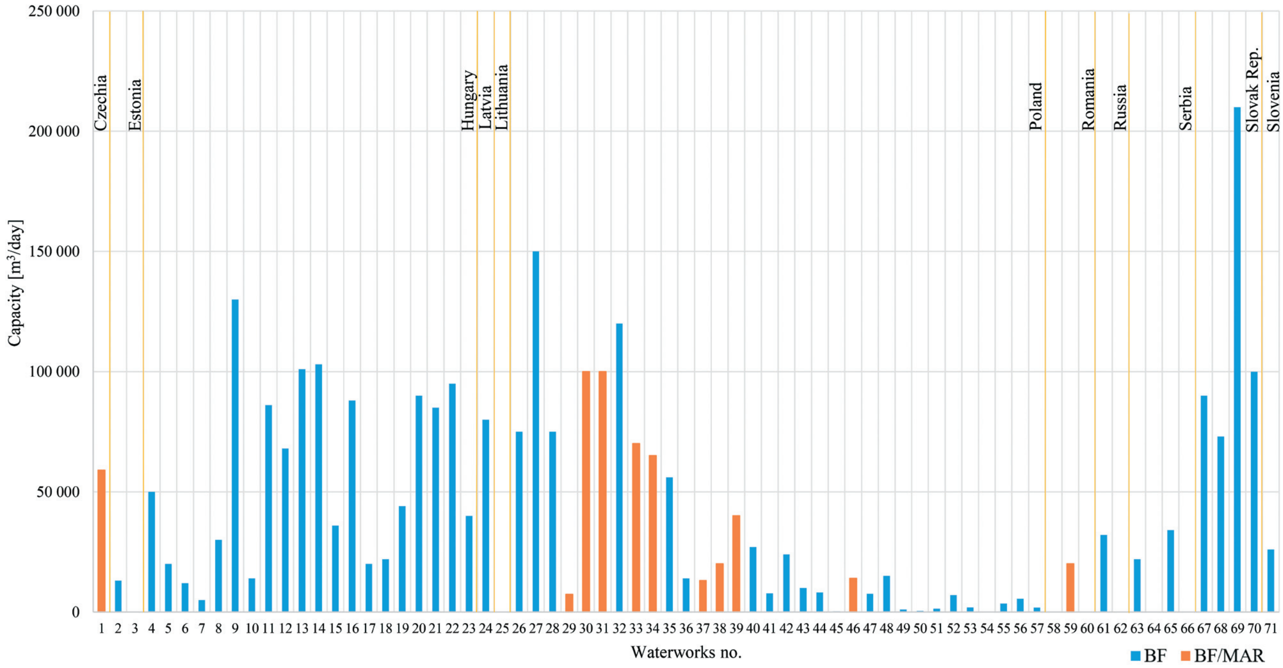

Fig. 4 Water production capacities of BF and BF/AR sites in Eastern Europe

Table 3 Mean and range of selected geohydraulic parameters at BF sites in Eastern Europe

		BF			Combined BF/AR		
Parameter	Unit	Median	Average	Range	Median	Average	Range
Capacity	m^3/d	25,000 (n = 52)	42,501 (n = 52)	38–210,000	62,000 (n = 12)	60,792 (n = 12)	5,500–150,000
Hydraulic conductivity	m/s	2.1×10^{-3} (n = 50)	2.7×10^{-3} (n = 50)	1.0×10^{-5} – 6.0×10^{-2}	5.3×10^{-4} (n = 12)	5.7×10^{-4} (n = 12)	4.0×10^{-5} – 4.0×10^{-3}
Aquifer thickness	m	10 (n = 50)	21 (n = 50)	2.5–120	12 (n =11)	16 (n =11)	5–44

capacity BF well fields prevail. The highest-capacity well fields are recorded in the Slovak Republic. The maximum value is 210,000 m^3/day in Rusovce, Slovak Republic. The number of BF schemes found in each country was higher than that of BF/AR combinations. Riverbank filtration is dominant; lake bank filtration being identified only at one site in Poland.

The smallest BF site has a capacity of only 38 m^3/day, and the largest BF site has a discharge capacity of 210,000 m^3/day. The smallest and the largest combined BF/AR site have a discharge capacity of 5,500 m^3/day and 150,000 m^3/day, respectively. The capacity of combined BF/AR sites was on average higher than that of sites with BF only. The average values of aquifer thickness and hydraulic conductivity are 21 m and $2.7*10^{-3}$ m/s, respectively, at BF sites and 16 m and $5.7*10^{-4}$ m/s, respectively, at BF/AR sites. The aquifer thickness and hydraulic conductivity of BF sites were on average higher than those of BF/AR sites (Table 3). The BF/AR sites show less variation in hydraulic conductivity and aquifer thickness (Fig. 5), but it has to be taken into account that the number of BF/AR sites (n = 11) is much lower than that of BF sites (n = 50). The highest values of both hydraulic conductivity and aquifer thickness were found at the BF well fields located in the Slovak Republic (waterworks no. 67–70).

Figs 6 and 7 show a comparison of hydraulic conductivity and aquifer thickness of the two types of well fields: BF and BF/AR. The hydraulic conductivity at 30% of the studied BF sites and at 83% of the studied BF/AR sites was lower than 1.0×10^{-3} m/s (Fig. 6). At BF and BF/AR sites, the most frequently recorded hydraulic conductivity ranges were 1.0×10^{-3}–1.0×10^{-2} m/s (62%) and 1.0×10^{-4} – 1.0×10^{-3} m/s (83%), respectively. At BF sites, the aquifer thickness in most cases was lower than 25 m (82%) (Fig. 7). The aquifer thickness at BF/AR sites was often found to be lower than 10 m (36.4%); however, at 90% of total sites, the thickness of the aquifer was below 20 m. The aquifer thickness range most frequently recorded at both BF and BF/AR sites was 5–10 m (42% of BF, 36% of BF/AR).

The quality of water varies with BF sites (Dragon *et al*. 2019; Hoppe-Jones *et al*. 2010; Nagy-Kovács *et al*. 2018; Szymonik, Lach 2013), and therefore various post-treatment steps are used. The most commonly used post-treatment step consisting of aera-

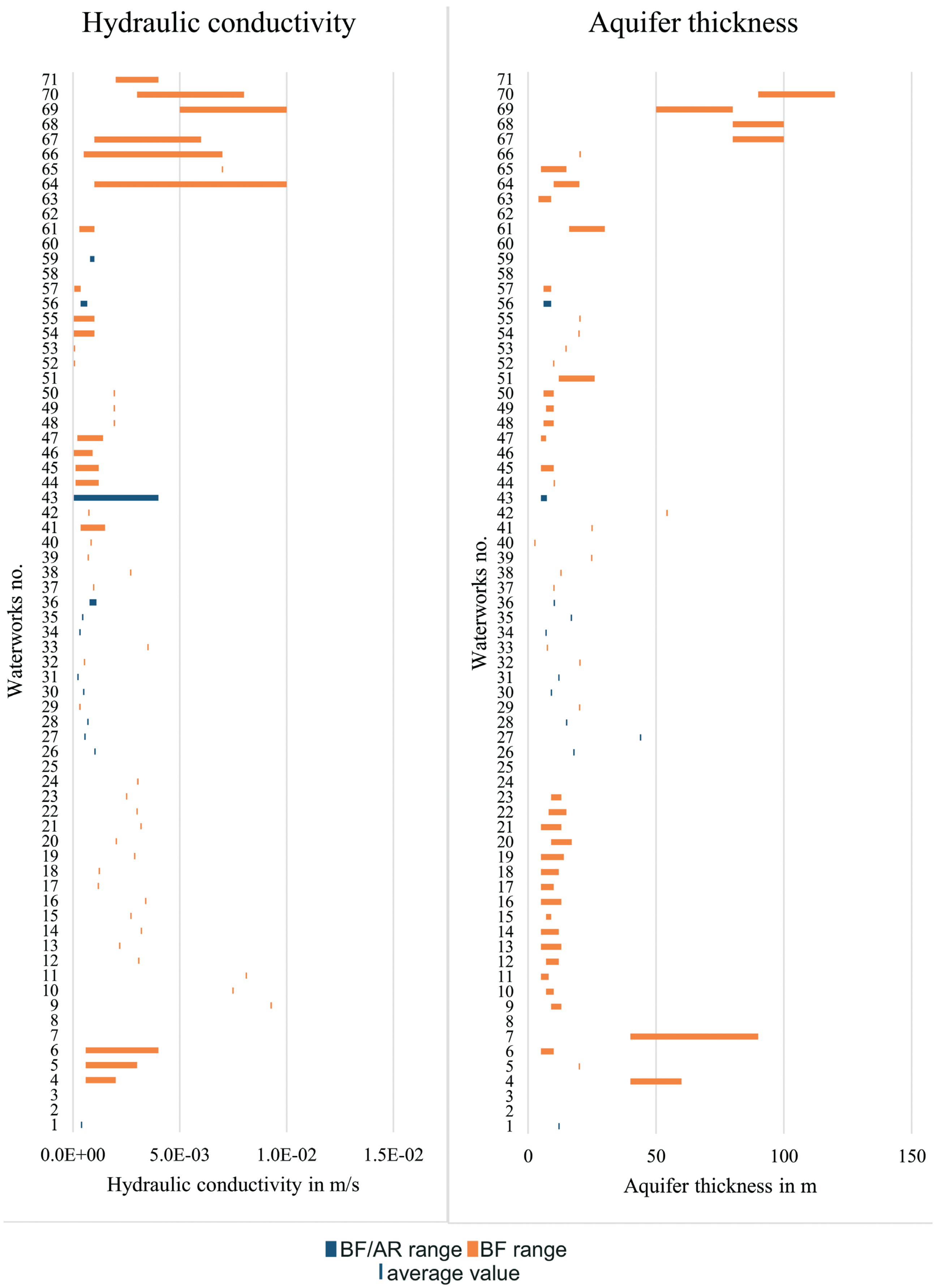

Fig. 5 Hydraulic conductivity and aquifer thickness of BF and BF/AR sites in Eastern Europe

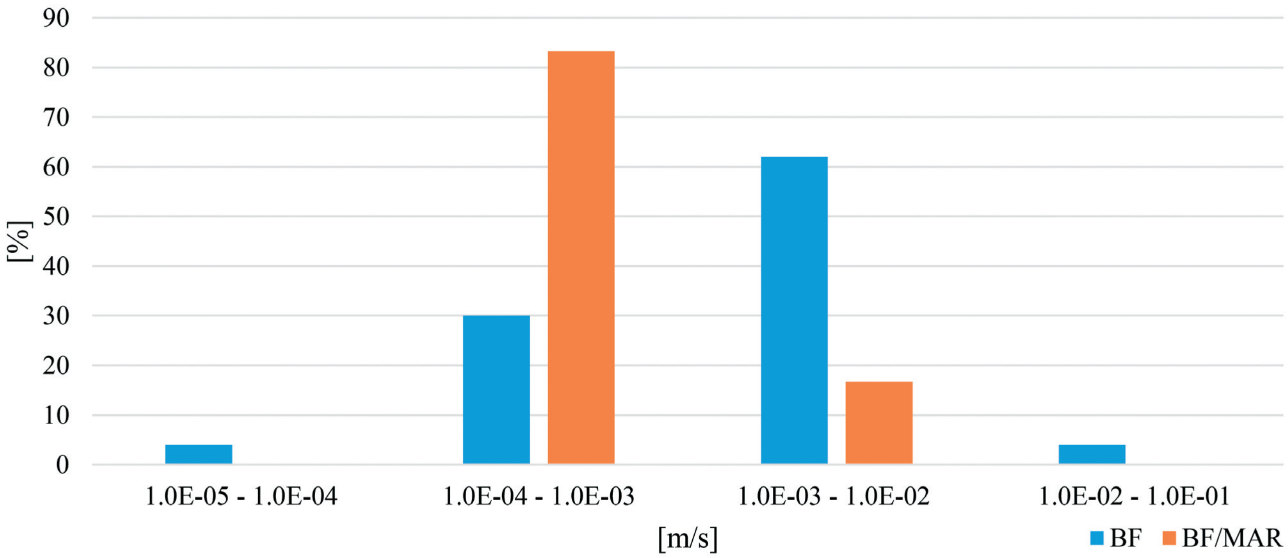

Fig. 6 Frequency of hydraulic conductivity values of BF and BF/AR sites in Eastern Europe

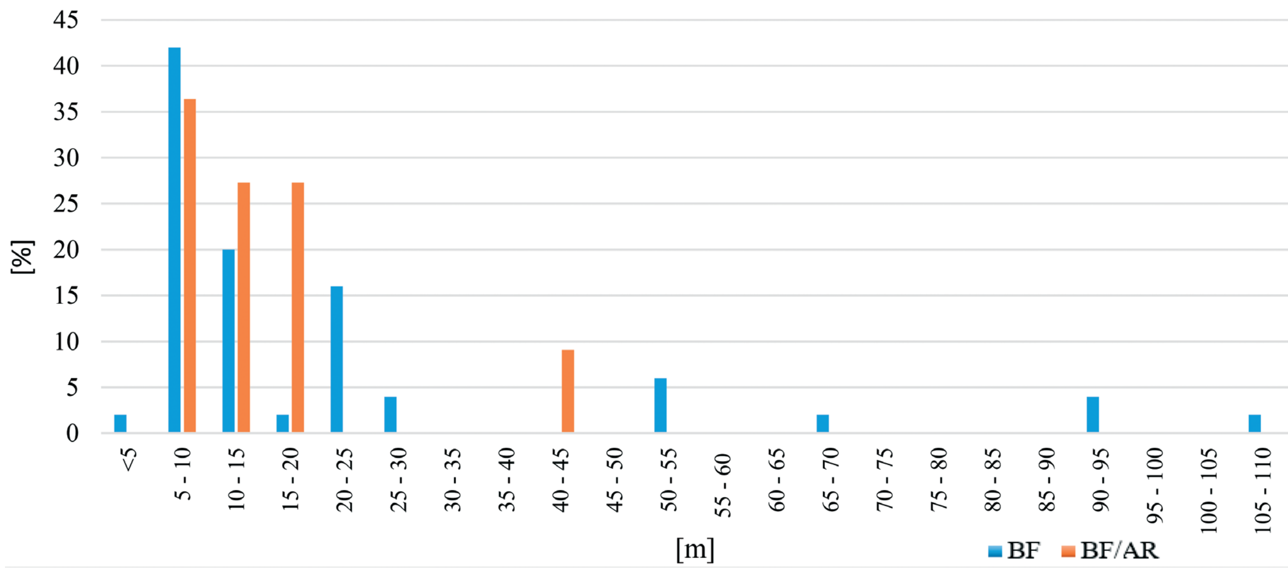

Fig. 7 Frequency of aquifer thickness of BF and BF/AR sites in Eastern Europe

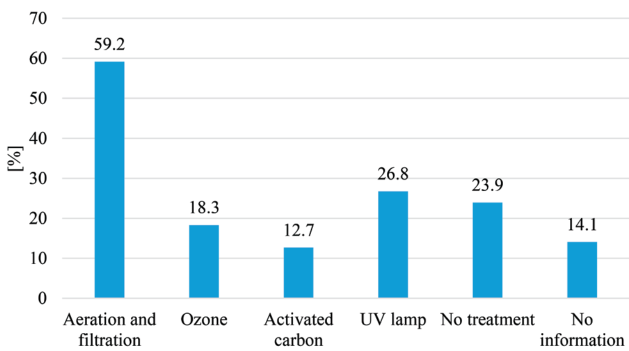

Fig. 8 Occurrence of post-treatment technologies at BF and BF/AR sites in Eastern Europe

tion – filtration – disinfection (Fig. 8) was recorded at 59% of all sites. The second most frequently used post-treatment was UV (27%). At some BF sites, UV is used only during extreme events (floods, droughts), when the subsurface passage may be not sufficient to guarantee complete attenuation of pathogens due to specific conditions facilitating migration of microorganisms (coarse-grained river bed and aquifer deposits). Our study showed that ozone is applied at 18% and activated carbon at 13% of the investigated sites. Six BF waterworks use ozone without activated carbon. The total number of sites, at which either UV or ozone without activated carbon is used for water treatment, account for 20% of the total number of the sites under study. Our study revealed that no treatment was implemented at 24% of the sites.

Examples of combined riverbank filtration and artificial recharge sites in Poland

Mosina-Krajkowo RBF site

The Mosina-Krajkowo well field supplies water to Poznań city and to the neighbouring towns and villages. The well field abstracts raw water from RBF along the Warta River (Table 4) and AR. The site is located in western Poland, 30 km from Poznań city. Hydrogeological conditions are favourable because sediments of two groundwater bodies, the Warszawa-Berlin ice-marginal valley aquifer (shallow) and the Wielkopolska buried valley aquifer (deep), overlap. The total thickness of the water-bearing sediments is 40 m. The sediments consist of Quaternary fine and medium sands in upper parts of the Warsaw–Berlin ice-marginal valley aquifer and Wielkopolska buried valley aquifer. In deeper parts of these aquifers, there is coarse sand and gravel. Hydraulic conductivity is 0.4–0.8 × 10^{-3} m/s. Below the aquifer, there are Neogene clays (Kruć *et al*. 2019; Przybyłek *et al*. 2017).

The Mosina-Krajkowo well field consists of (Fig. 9):

– a 7150 m long terrace gallery (RBF-f) containing 56 vertical wells spaced 100–150 m apart with their depth ranging from 38.0 to 52.0 m and capacity from 50 to 150 m^3/h;

– Krajkowska Island, an area separated by water reservoirs, i.e., the Warta River and an artificial protective channel. Krajkowska Island contains:

1. RBF-c – a 1980 m long gallery on the protective embankment containing 29 vertical wells spaced 45–90 m apart with their depth ranging from 35.0 to 46.5 m and capacity from 90 to 120 m^3/h, supplied with induced infiltration water from the Warta River, infiltration water constituting 70–80%;
2. AR – a gallery of 11 vertical wells with their depth ranging from 20 to 25 m and a capacity ranging from 40 to 45 m^3/h, supplied with water from 3 artificially formed ponds and one natural pond, which are, in their turn, fed with water from the Warta River via pipelines;
3. HW – a horizontal collector well – consisting of a pumping station and a collector well, with a diameter of 8 m and a depth of 12 m, from which 8 horizontal drains were derived, with a total active length of 718 m, arranged at a depth of 5 m under the bottom of the Warta River (Górski *et al*. 2011).

The quality of water in separate well field varies. Table 5 shows differences in the quality of water from HW, AR, and RBF-c. The pollutants removal percentage is the /result of attenuation processes in the riverbed and along the flow path of the infiltrate in the aquifer and mixing with land-side groundwater.

The water treatment train consists of cascade aeration, rapid sand filtration, ozonation, granulated activated carbon (GAC) filtration and disinfection with ClO_2 and NaOCl. The use of ozonation and GAC is mainly aimed at reducing natural organic matter (NOM) so as to ensure the biological stability of water in the distribution system and to diminish the chemical demand for ClO_2 and NaOCl that are used for water disinfection.

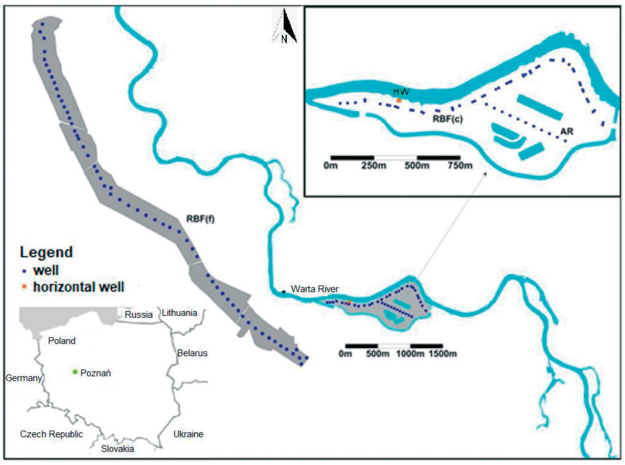

Fig. 9 Mosina-Krajkowo well field situation map (Przybyłek *et al*. 2017)

Table 4 Hydrological characteristics of the Warta River

Warta River	
Parameter	Value
Width	55–70 m
Depth	1.1–2.1 m
Gradient	0.18–0.19‰
Flow velocity	0.73 m/s (0.22–0.76 m/s)
Turbidity	8.6 NTU (4.2–30 NTU)
TSS	mg/l (1.6–42 mg/l)

Table 5 Differences in water quality from HW, AR and RBF-c in Mosina–Krajkowo wells field, 2017–2018

Parameter	Unit	Warta River	Horizontal well	Percentage removal	AR wells	Percentage removal	RBF-c wells	Percentage removal
TOC	mg/l	14.25	10.58	25.8	5.17	63.7	11.07	22.3
COD Mn	mg/l	10.4	6.2	40.4	3.72	64.2	5.5	47.1
NO_3^-	mg/l	11.6	10.6	8.6	0.29	97.5	2.6	77.6
NH_4^+	mg/l	0.42	0.28	33.3	0.57	–35.7	0.28	33.3
Total hardness	mmol/l	2.4	2.35	2.1	2.56	–6.7	2.65	–10.6
Fe	mg/l	0.55	0.15	72.7	2.41	–338	0.92	–67.3
Mn	mg/l	0.14	0.18	–28.6	0.67	–377	0.52	–271
Total coliforms	MPN/100ml	700,000	1,670	99.8	0.3	99.9	5	100

Dębina artificial recharge and riverbank filtration site

The Dębina well field is located in the flood plain area of the Warta River valley in the southern part of Poznan city. The recharge of the aquifer proceeds mainly by water infiltration from artificial ponds, which are recharged with water from the Warta River. Additionally, RBF is used for water production. The well field was built in the 3.2 km long section of the Warta River valley, where the maximum thickness of Quaternary deposits (mainly sands and gravels) reaches 20 m. The aquifer bottom consists of Neogene clays. The hydraulic conductivity of the aquifer ranges between 2.2 and 5.1 × 10^{-4} m/s. The well field contains (Fig. 10):

–34 infiltration ponds (20–25 m in width and 150–450 m in length, with a depth of 180 cm) located in 3 lines parallel to the river,

–3 well galleries with siphon systems located in 3 lines parallel to the river and infiltration ponds. The wells are located at a distance of approx. 75 m from infiltration ponds and the Warta River, which indicates that the travel time of water from pond/river to the wells is 30 days.

As the well field is crossed by A2 highway, 150 m wide protective zones were established on both sides of the highway. Moreover, to protect the well field against potential contamination from the highway, there were 6 protective ponds forming hydraulic barriers built parallel to the highway. The well field capacity is ~78,800 m^3/d, and the water budget consists of the water infiltrated from the ponds (60–76%), riverbank filtrate from the wells located between the river and the first line of ponds (16–27%), and groundwater (2.7–12%).

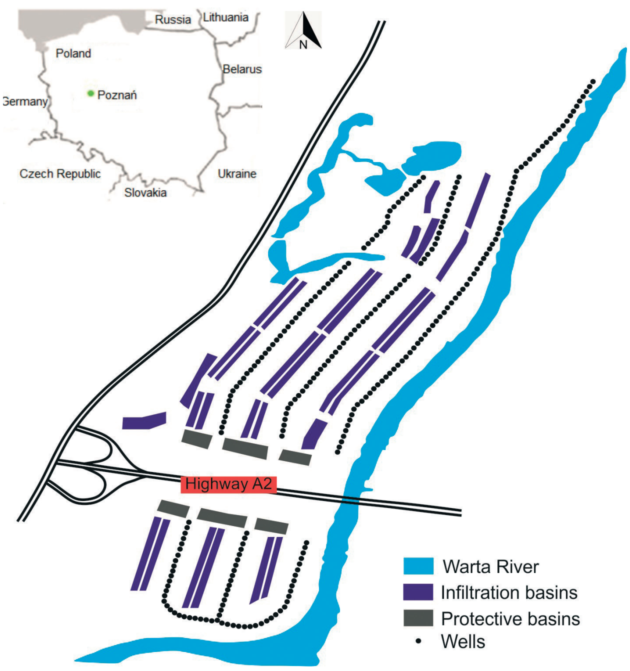

Fig. 10 Dębina well field location map (Przybyłek 2009)

Table 6 shows a comparison of the physico-chemical parameters of the abstracted water and those of the river water.

Water treatment in RBF and AR results in a strong removal of bacteria, nitrate, ammonium as well as total organic carbon (TOC) and colour. The post-treatment includes aeration and rapid sand filtration. UV treatment and chlorination is used for water disinfection.

DISCUSSION

The built-up database on BF/AR sites can supplement the existing database (IGRAC 2017) with regional data from Eastern Europe. Until now, only limited information on this part of Europe was available.

Our study collected data on geohydraulic conditions and post-treatment in Eastern Europe. The data were collected using three approaches: direct communication with investigators, literature research and manual identification of sites along major rivers and lakes using maps, the first of which proved to be the most efficient. However, information transfer was rather complicated due to language barriers, difficulties in establishing contacts and getting permission for data use in the project. Few publications and archival data provided useful information on previous work and ongoing research in the field of BF. Access to the databases of Polish hydrogeology (available only in Polish) allowed collecting data on a large number of BF sites in Poland. Similarly, some input was provided by the manual study of maps. The approach could have been more efficient if a larger number of wa-

Table 6. Quality parameters of water from the Warta River and of abstracted water in Dębina well field, Poland

Parameter	Unit	Warta River	Raw water
Temperature	°C	8.9	11.9
Turbidity	NTU	7.5	2.4
Colour	mg Pt/l	25.6	15.8
pH	–	7.97	7.36
NH_4^+	mg/l	0.24	0.13
NO_2^-	mg/l	0.064	0.032
NO_3^-	mg/l	12.6	3.6
Fe	mg/l	0.54	0.5
Mn	mg/l	0.11	0.33
Cl^-	mg/l	42.8	42
Total hardness	mmol/l	9.4	9.8
Alkalinity	mmol/l	3.2	3.4
TOC	mg/l	8.0	4.5
Sulphate	mg/l	66.8	74.4
Dissolved oxygen	mg/l	10.4	3.4
Total coliforms	MPN/100 ml	10,473	1
Clostridium	MPN/100 ml	130	0–2

terworks administrators had provided information on water abstraction rates and post-treatment technologies on their webpages. Thus, many sites having wells near surface water bodies could not be included in the database because it was not clear to what extent they are using BF for water supply. The European Commission has already requested more transparency and greater availability of the web-based information on water sector. Information on geohydraulic parameters is indispensable for the identification of suitable conditions for the designation of BF sites. Additionally, the presented database provides information on commonly applied water treatment techniques. At most sites, the use of post-treatment technologies is not extensive. Most of the well fields in operation have undergone just the basic treatment, which includes aeration – filtration – disinfection. The use of BF/AR as a first treatment step obviously simplifies the process of drinking water production.

The current research was focused on two types of sites: BF and AR. Two sites in Poland, Mosina-Krajkowo and Dębina, were described in more detail. Both schemes are located on the Warta River and are used for treating the water that is supplied to the same city. However, they are based on two above-discussed different technologies: BF and AR. In this study, geohydraulic conditions, changes in water quality and the post-treatment applied were documented.

The collected data can be helpful in designing and modernizing BF sites. For more comprehensive assessment of potential pollution attenuation rates, prediction of raw water quality and the required post-treatment, the database supplementation should be continued by adding information on distances between rivers and wells, water travel times or water quality.

CONCLUSIONS

There are many BF or AR sites in Eastern Europe. Data on 71 BF and combined BF/AR sites have been compiled and discussed. The well fields under study are mainly located along rivers. The use of a particular water treatment technology was found to be water demand- dependent. The use of BF in combination with AR was typically recorded at the sites with higher production capacities required. The combined BF/AR sites represent 18% of all the sites studied.

Both at BF and BF/AR sites, water production capacities were found to vary considerably. Discharge capacities also proved to vary within a very wide range both at BF and AR sites (38 m^3/day – 210,000 m^3/day at the BF sites and, 5,500–150,000 m^3/day at the BF/AR sites). Obviously, BF is widely used at different scales, ranging from village water supply to water supply of large cities. The average aquifer thickness and average hydraulic conductivity were found to be higher at BF sites (21 m and 2.7×10^{-3} m/s) than at BF/AR combination sites (16 m and 5.7×10^{-4} m/s). The hydraulic conductivity rates most frequently recorded at BF and BF/AR sites were 1.0×10^{-3}–1.0×10^{-2} m/s (62%) and 1.0×10^{-4}–1.0×10^{-3} at (83%), respectively. Our study showed that most often the aquifer thickness both at BF and BF/AR sites varied within a small range of 5–10 m (42% of BF, 36% of BF/AR).

Our study revealed that most sites had not undergone extensive post-treatment. At 59% of the investigated BF sites, conventional post-treatment, including aeration, filtration, disinfection, which is commonly applied in groundwater treatment, was used. At 20% of the sites under investigation, for the removal of pathogen, either UV or ozone treatment was used. As demonstrated by the EU AquaNES project, instead of advanced treatment with ozone, it is possible to use other techniques for the removal of organic compounds or pathogens, e.g. BF-membrane filtration. The wide range of production capacities shows the applicability of BF as a natural treatment component both for small communities and large metropolitan cities. Surprisingly, the communication with a large number of water supply administrators and even waterworks employees revealed that they were not aware of the benefits that BF implementation provides or even of whether BF was used by their company or at their sites.

The database presented herein covers 48 BF sites that are not yet listed in the Global Inventory of Managed Aquifer Recharge Schemes (IGRAC 2017). The authors suggest incorporating the data obtained in the IGRAC inventory.

FUNDING AND ACKNOWLEDGMENTS

This research was completed with support from the AquaNES project. This project received funding from the European Union's Horizon 2020 Research and Innovation Program under the grant agreement no. 689450. The authors are grateful to two anonymous reviewers for valuable remarks and suggestions that allowed improving the manuscript.

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