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Impact of wildfires on the drinking water catchment for the capital area of Iceland – a case study†

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Climate change is leading to an increase in extreme weather events in the Arctic, which can significantly affect both the quality and availability of drinking water. Prolonged droughts lower groundwater levels and reduce soil moisture that elevates the risk of wildfires, which can contaminate water resources and damage water supply infrastructure. This case study examines the impact of wildfires on water quality in porous volcanic strata in the Arctic. The primary water extraction area for the capital region of Iceland supplies drinking water to six municipalities, representing approximately 64% of the country's population. The water source is mainly located in a postglacial porous lava field with thin volcanic strata and limited surface water. On May 4th, 2021, a large wildfire occurred in the watershed following a prolonged drought, burning 56.5 hectares of land. Three of the water intake zones for the capital region are situated 300 meters to a few kilometres from the fire-affected area. Water quality monitoring data from these zones, covering the period 2011–2023 and comprising 47 samples (28 pre-fire and 19 post-fire), were analysed. The results show the presence of polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs), as well as an increase in certain metals after the wildfire. The total concentration of the five detected PAHs ranged from 1.1 to 7.3 ng l^{-1}, with PAHs detected up to five months post-wildfire. These were predominantly five- or six-ring carcinogenic PAHs, though levels remained well below the parametric values set by Icelandic drinking water regulations. Some VOCs were also detected after the wildfire, albeit mostly at a later stage. Additionally, several metals were found in concentrations up to nearly six times higher than the median values recorded from 2011 to 2020. These findings suggest that groundwater quality is vulnerable to contamination following wildfires, underscoring a critical knowledge gap regarding the impacts of climate change on the water sector and the need for enhanced risk mitigation strategies.

Environmental significance

Climate change is leading to an increase in extreme weather events, which can result in long-lasting droughts that increase the risk of wildfires. Wildfires are now more frequent in the Arctic, including Iceland. This study investigates the impact of wildfires on water quality in a groundwater catchment that serves 64% of the population of Iceland and lessons learned for future risk mitigation. The literature on wildfires in the Arctic is limited and the need for more research to understand current and future risks and how to adapt has been recognized.

Introduction

Climate change is expected to have various impacts on water supplies and drinking water quality worldwide. There are predominantly three climate change-related factors that will impact water quality: an increase in temperature; a rise in the sea level; and seasonal and regional changes in precipitation, both in quantity and intensity.[1,2] An increase in temperature will lead to more frequent unusual weather patterns, such as more rainfall, which increases water reserves, and more droughts and thus water shortages that can result in wildfires.[3,4] Wildfires in the Arctic are now more frequent as the Arctic is warming faster than the rest of the globe and evidence indicates that northern ecosystems will become increasingly vulnerable to wildfires and their impact.[5–9] During wildfires, a significant number of organic compounds and other elements such as metals and nutrients are released, which can result in the contamination of otherwise less impacted environments in the Arctic.[10]

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Worldwide, wildfires are considered a primary source of PAHs in Arctic ecosystems and the contribution of wildfires to PAHs in the Arctic has increased significantly since 2011.[9,11] PAHs have been shown to have a great impact on microorganisms, humans, animals, and plants.[12] Gosden *et al.*[13] studied wildfires in western Greenland for the period 1995–2020, using satellite remote sensing, and identified 21 tundra fires. The first fire was recorded in 2008 and fires have occurred in most years since then, most often in July or August during periods of warm, dry weather. The Icelandic Institute of Natural History has registered wildfires in Iceland since 2006 and maps non-urban areas affected by wildfires as well as studying their effects on the biota. The largest recorded wildfire in Iceland's history raged in the sedges and shrubs of a wetland area in western Iceland from 30 March to 1 April 2006. The area affected by the fire was 6700 ha. Meteorological data from the area show that no rain had fallen there in the 10 days prior to the fire.[14] This large fire led to the start of systematic registering and studying of larger wildfires in Iceland. In the period 2006–2023, 24 wildfires (>0.5 ha) were registered, mostly (73%) occurring in the 3 spring months of March to May. Research on the impact of the large wildfire in 2006 on the aquatic environment a year later did not indicate a significant long-lasting impact on lakes, either in terms of chemical or physical elements or the biota.[15] A new threat is wildfires near volcanic eruptions on the Reykjanes peninsula,[16] where volcano-tectonic reactivation of the Reykjanes Peninsula has so far accounted for nine eruptions in the area (6.9.2024), which have initiated several wildfires burning vegetation on lava fields on which moss is dominant.[17]

During wildfires, organic chemical contaminants, such as PAHs, are deposited into the soil from burning vegetation. Major and trace elements, such as heavy metals, are highly concentrated in the ash layer that remains following major wildfires.[18,19] The PAHs produced during a fire can vary and depend on the vegetation as well as the fire severity and longevity. Smoke from wildfires consists of permanent gases, VOCs, semi-volatile organic compounds (SVOCs) and particulate matter (PM). Gases are mostly CO_2 and NO_x, the VOCs are the BTEX group (benzene, toluene, ethylbenzene and xylene), and the SVOCs include PAHs.[20] Wildfires have also been shown to contaminate the distribution system by thermal damage to plastic pipes, which contaminates water with VOCs and SVOCs.[21–23] Apart from the devastating short-term effect of wildfires on biota and water quality, depending on the exposure level, the concentration of the toxins emitted during wildfires can damage the health of both firefighters and other people in the vicinity of the fire. Airborne and dermal exposure to some of those compounds is known to have cytotoxic and/or mutagenic properties and some are carcinogenic.[24]

Water retrieval in the Arctic and subarctic is mainly from surface sources such as lakes, rivers and icebergs.[25] Water harnessing of all regulated water supplies in Greenland is 100% from surface water and in the Faroe Islands it is 93%, whereas in Iceland it is 95% from groundwater.[26] Harper *et al.* [27] conducted a literature review on the drinking water system and health outcomes in the context of climate change in the Circumpolar North, in light of the existing high burden of waterborne diseases in those areas and concluded that more research is needed to understand current and future risks and how to adapt. This research gap is evident when a literature review is done for contamination by PAHs from wildfires on groundwater in the Arctic. A non-arctic example is the recent increase in the frequency of wildfires in Portugal with impacts on the ecosystem and sometimes on groundwater.[28–30] A large wildfire in central Portugal in the Caramulo Mountains in August 2013 resulted in 14 of the 16 measured PAHs being detected in groundwater, especially naphthalene and benzo(*ghi*)perylene. In October 2017, a large wildfire took place in the Braga Region in NW Portugal in a water catchment area for small public water supplies in a peri-urban area. Six months after the wildfire, and after the first intense rain event, carcinogenic PAHs began to be detected in considerable concentrations in groundwater, though parametric values were not exceeded.[31–33]

A recent review by Paul *et al.*[34] on the impact of wildfires on water quality reports that nutrients, organic chemicals and metallic compounds increased in burned watersheds, sometimes by orders of magnitude over pre-fire conditions. Some exceeded guideline values for aquatic life criteria or drinking water regulations. The duration of effects reported was less than five years. Campos *et al.*[35] examined the impact of wildfires in Portugal on the levels of V, Mn, Co, Ni, Cu, Cd and Pb in soil and ashes in burned pine (*Pinus pinaster* Ait) and eucalypt (*Eucalyptus globulus* Labill) forests in central Portugal. The concentrations of V, Mn, Ni, Cd, and Pb were consistently elevated in burned areas compared to unburned areas, and some were persistently higher in pine forests than in eucalypt forests. Pennino *et al.*[36] examined post-wildfire effects on drinking water quality by calculating the exceedance of the maximum contaminant level (MCL) for 253 US catchments with wildfire incidents and concluded that wildfires are associated with increased levels of contamination in drinking water that can last for multiple years. After using data from 159 fires in the US, Rust *et al.*[18] also concluded that there was a strong initial increase in nutrients or metals that was not detectable 5 years post-fire. Kieta *et al.*[19] reported that long-term studies have shown that the most severe impact occurs one to three years after a fire, but on the other hand, little research has been undertaken to determine the long-term persistence of PAHs and metals in the aquatic environment after wildfires. Sham *et al.* [37] presented a survey on the impacts of wildfires on 27 drinking water systems in the USA that had experienced or are at risk of effects from wildfires. The results emphasized the importance of risk management and an emergency response plan, including a post-fire monitoring strategy, efforts to reduce fuel through prescribed burns and clear cutting, maintaining access to vulnerable areas to control fire hazards, protecting the infrastructure, and collaboration with other drinking water utilities and stakeholders. The survey also identified some topics that merit further research, including the effects of wildfires on water quality and treatability and on watershed resiliency in different geographies, ecosystems and climate regions.

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Wildfires are increasingly prevalent worldwide, representing a significant indicator of climate change, with 2023 recorded as the hottest year on record.[38] In Iceland, the frequency of wildfires has been rising, raising concerns about the vulnerability of groundwater in affected areas, as untreated groundwater serves as the primary source of water supplies. The objectives of this study are threefold: first, to assess the impact of wildfires on water quality; second, to evaluate whether hydrometeorological data preceding wildfires can predict wildfire risk; and third, to summarize the lessons learned from the wildfire for future risk mitigation.

Study area

Iceland, an island in the North-Atlantic Ocean (about 103 000 km^2), belongs to the Arctic according to the AMAP definition.[39] It is in the ecoregion of boreal birch forests and alpine tundra and is entirely volcanic and composed of basaltic rock. It is predicted that climate change will increase temperatures in Iceland by 1.3–2.3 °C until the middle of the century and that the warming will be greater in winter than in summer.[40] The primary water source is groundwater (95%), with a universal piped supply to dwellings.[26,41] The warming in Iceland is causing permafrost thawing and triggering landslides.[42] Gunnarsdottir *et al.*[43] reported landslides damaging water supply infrastructure in Iceland. The paper includes a risk assessment of 179 water intakes in mountainous North-East Iceland and estimates that 40 (22%) are at medium to high risk for damage because of landslides. There are indications that the intensity of rainfall has increased and, despite the increase in total rainfall, the number of dry days may also increase.[40]

The groundwater resources for drinking water for the capital region of Iceland are in the greater Heidmork area (see Fig. 1). The area supplies water to six municipalities—Reykjavik, Kopavogur, Gardabaer, Hafnarfjordur, Mosfellsbaer, and Seltjarnarnes—serving 64% of the population of Iceland (about 230 thousand residents) and is harnessed by six publicly owned water utilities with a yearly average of about 1100 l s^{-1}.[44] Furthermore, the area is designated as a nature reserve and serves as the largest outdoor recreational area in the vicinity of the city, covering approximately 32 square kilometers. Almost 90% of the area is vegetated land, of which about 20% is cultivated woodland and 20% is wild birch forest and scrub.[45] According to the NDVI (Normalized Difference Vegetation Index), measured since 1982, there has been a great increase in vegetation in the northern latitudes, including Iceland, since the 1980s.[40,46]

A protected catchment zone is defined in Heidmork according to Icelandic regulation (796/1999) and the EU Water Framework Directive (Directive, 2000/60/EC). It is divided into four zones: water intake, primary (near zone), secondary (distance zone), and safety zones. Regulation no. 796 from 1999, together with later additional regulations related to drinking water protection (555/2015), restricts land use and the use of chemicals in Heidmork protection zones. The water source is in a postglacial porous lava field (VK and G–J) and in older

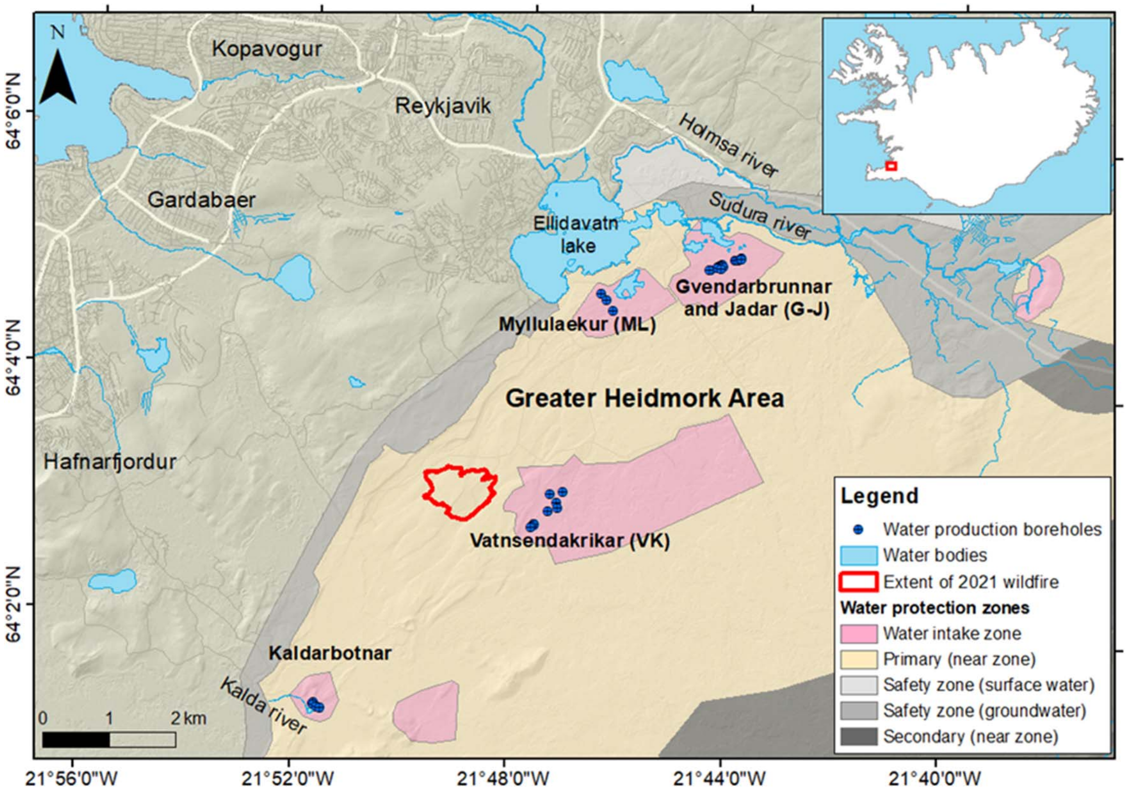

Fig. 1 The greater Heidmork area – the water protection area for the capital region. Drinking water production boreholes are shown. The wildfire area is marked as red (based on data from the Icelandic Institute of Natural History).

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interglacial lava fields (ML) with thin volcanic strata. These areas have limited surface water as most water seeps into the ground. There are three rivers in the area, one at the south boundary of the primary zone (Kalda river) and two at the northern boundary (Suðura river and Holmsa river), and several lakes are at the boundaries. The size of the water protection area is around 250 km^2, of which 9 km^2 make up the water intake zones and 100 km^2 the primary zone.[47]

Groundwater flows from the mountain area south-east of Heidmork towards the lowlands in the north-west. At Vatnsendakrikar (VK), harnessed by Veitur Utilities and Kopavogur Utility (also delivering water to the water utility in Gardabaer), the groundwater stream divides, as part of the stream flows north and north-west to Myllulækur (ML) and Gvendarbrunnar–Jadar (G–J), and part flows south-west to Kaldarbotnar, harnessed by Hafnarfjordur.[48]

Veitur Utilities provides drinking water for the capital Reykjavik as well as delivering to the municipalities of Seltjarnarnes and Mosfellsbaer, in all serving around 147 thousand people in 2021 (with an annual average production of 739 l s^{-1}). Groundwater is harnessed through eighteen production boreholes in the three water intake areas. In some boreholes, the groundwater level is close to the surface and therefore more vulnerable to contamination, especially in production zones G–J and ML (Table 1).

Methods

Water quality data

Major elements, trace elements and organic compounds are monitored at least twice a year in each of the three production zones used by the Veitur Utilities in Heidmork and twice in the distribution network in adherence to the Icelandic drinking water regulation (536/2001). Only samples taken from the water protection zones are used in this research, with one exception.

Drinking water is sampled by the Reykjavik Public Health Authority and analysed by the accredited laboratory ALS Scandinavia AB in Sweden (**https://www.alsglobal.se/en**). ALS Scandinavia is using the following methods: W-VOCGMS01 for BTEX (US EPA 624, 8260, 8015, and CSN EN ISO 10301, 11423, 156809), W-GCS-6/GA for PAH (DIN 38407-39), OV-6b_6434 for VOC (AK210), and W-SFMS-5A and W-AES-17 for metals (SS-EN ISO 11885:2009 and SS-EN ISO 17294-2:2016). Twenty-three metals and metalloids, 12 non-metals and 37 organic compounds (16 PAHs and 21 VOCs including the BTEX benzene, toluene, ethylbenzene, and xylenes), along with indicator parameters, are measured in regular samplings. This study includes analysis of twenty-eight monitoring results from before the fire, in the period 2011–2020, and nineteen after the fire until the end of 2023 (Table 2), with a few exceptions where either the detection limit was too high for measuring natural levels (B, Se, and F) or monitoring started later (Li). One sample from the distribution network (DN Laxalon) was also added as sampled twenty days after the fire and not far from the production zones. All 76 parameters analyzed were tested for significant change before and after the wildfire using a *t*-test: two-sample assuming unequal variances. The parameters showing significantly increased concentration or a sign of sporadic increase, though not significant, are plotted.

Hydrometeorological data

Precipitation data from Reykjavik were received from the Icelandic Meteorological Office, both for the period around the fire (1.10.2020–30.9.2021) and for the 30 year average (1991–2020). The data were aggregated to get cumulative monthly precipitation. Records of volumetric soil water content at 15 cm depth, measured in soil by the Icelandic Meteorological Office for Veitur within an open field and forested area in zone ML, are available for times before and after the fire. Ten-minute average

Table 1 Intake areas for Veitur Utilities

Production zone	Bore-holes no.	Boreholes monitored	Water harnessed[a] in 2021 (l s^{-1})	Depth of boreholes (m)	Elevation at boreholes (m a.s.l.)	Groundwater level (m)
Gvendarbrunnar–Jadar (G–J)	10	V1, V3, V4, V5, V10, V19, V23	386	8–64	81–90	0–10
Myllulaekur (ML)	3	V12, V13, V14	143	51–104	86–92	4–14
Vatnsendakrikar (VK)	5	VK1, VK2, VK5	210	97–136	145–150	23–34
Total	**18**		**739**			

[a] Yearly average.

Table 2 Sample results before and after the fire in each of the production zones (2011–2023)

Data/zone	Gvendarbrunnar and Jadar G–J	Myllulaekur ML	Vatnsendakrikar VK	Laxalon DN[a]	SUM
Pre-fire	8	9	11	0	28
Post-fire	9	3	6	1	19
Total	**17**	**12**	**17**	**1**	**47**

[a] DN = distribution network.

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values were used. Records of the historical groundwater level in the VK production zone east of the wildfire were available from 2008. Daily averages from borehole VK-1 were used.

Interview

A semi-structured interview was conducted with the Metropolitan Fire Department on 11.5.2023. The interview focused on two main topics: (1) the sequence of events concerning the wildfire in Heidmork and (2) lessons learned to increase resilience. The questionnaire is shown in the ESI† to this article.

Results and discussion

Impact on water quality

Results from sampling taken a week after the fire (May 11) from boreholes in the two water intake zones VK and G–J showed various PAHs and some VOCs following the fire (Fig. 2 and Table 4). Although the analysis of organic compounds is part of the routine monitoring program at the Heidmork production site, the detection limits of the employed methods were, most often, up to an order of magnitude higher prior to the wildfire compared to post-wildfire. The detection limit for all organic chemicals is shown in the ESI† to this article. None of the pre-fire samples exceeded the detection limits for PAHs.

Five of the 16 priority PAHs were above the detection limit in zones G–J and VK within weeks of the wildfire (ML was not measured then). These include naphthalene (NAP) and phenanthrene (Phe) with two or three benzene rings; these are classified as non-carcinogenic. Dibenz(*ah*)anthracene (DahA), benzo(*ghi*)perylene (BghiP) and indeno(1,2,3-*cd*) pyrene (Ind), in turn, are carcinogens with 5 to 6 benzene rings.[49] While some of the concentrations were close to the detection limit, they were always well below health limits. The highest concentrations were two to three times the detection limit. The fact that the concentrations mostly exceeded detection limits one week after the fire, coinciding with an increase in some metal concentrations (Fig. 3), supports that the pollution is linked to the wildfire. The total sum of the five PAHs detected a week after the wildfire ranged from 1.1 to 7.3 ng l^{-1}. The three carcinogenic PAHs were only detected in borehole V4 in the lower intake area (G–J), where the groundwater level is only 1–10 m (Table 1). Because of the lack of sampling after the precipitation at the end of May (29th, 2021), it is difficult to know the influence of infiltration into groundwater aquifers and thus the phase-out of the PAH contamination.

Six metals, barium (Ba), cobalt (Co), lithium (Li), molybdenum (Mo), magnesium (Mg) and strontium (Sr), were measured in two to nearly six-fold higher concentrations after the fire compared to the median value (Fig. 3 and Table 3). Some increases were short-lived, namely Co, Li, Mg and Mo, while Ba and Sr showed a tendency for longer-lasting impacts and there was a significant post-fire increase in concentration in both ($p < 0.05$). Arsenic (As) and chloride (Cl) also have significantly higher post-fire concentrations. However, this does not seem to be related to the wildfire as shown in Fig. 3. It is noted that the elevated concentration of

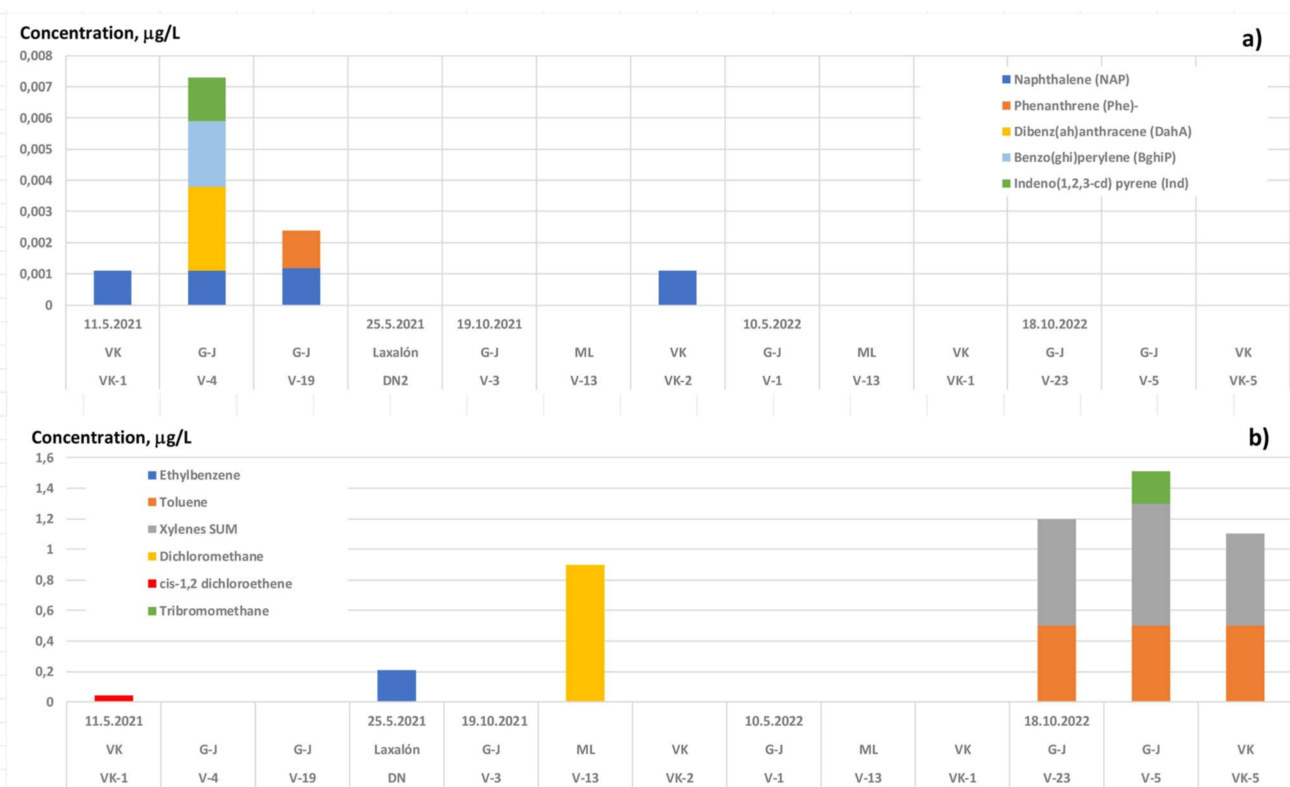

Fig. 2 PAHs (a) and VOCs (b) detected in samples from 11.5.2021 until 18.10.2022 (VK = Vatnsendakrikar, G–J = Gvendarbrunnar–Jadar, DN = distribution network, and ML = Myllulaekur).

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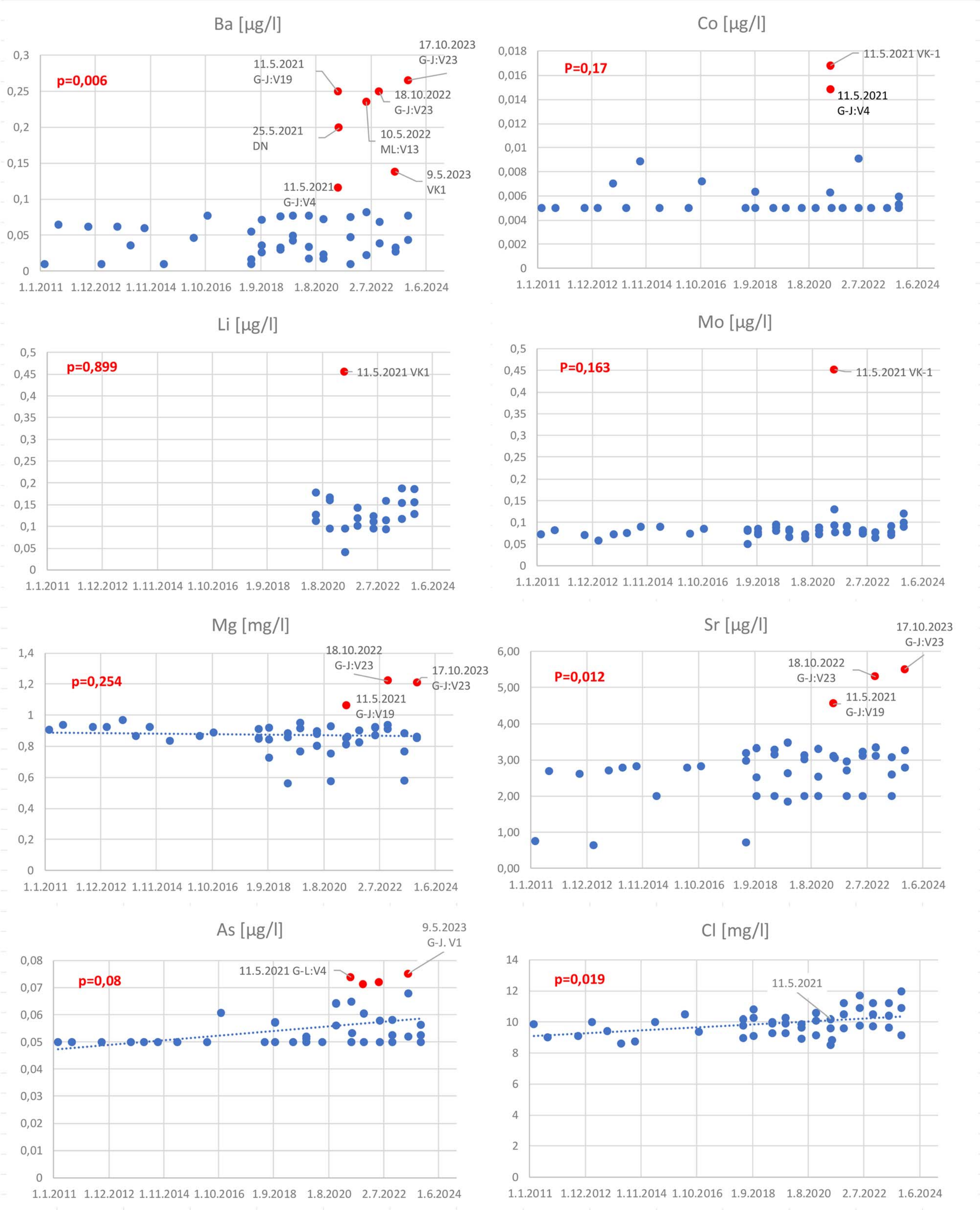

Fig. 3 Eight elements measured in samples taken between 2011 and 2023 showing either a temporary increase after the fire or a significant post-fire increase.

As might be due to volcanic activity in the Reykjanes peninsula or steam from a geothermal power plant less than 20 km away. Steam from the geothermal power plant has been shown to contain an elevated level of arsenic and geothermal water from the system has been reported to contain 92–104 µg l^{-1}.[50,51]

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Table 3 Result from the *t*-test. Mean, variance and significance of selected elements in water before and after the wildfire

		Unit	Time	Observation	Mean	Variance	df	$P(T \leq t)$tw
1	Barium, Ba	$\mu g\ l^{-1}$	Pre-fire	28	0.043	0.001	19	0.006
			Post-fire	18	0.110	0.008		
2	Cobalt, Co	$\mu g\ l^{-1}$	Pre-fire	28	0.005	8.28×10^{-7}	20	0.170
			Post-fire	19	0.006	1.18×10^{-5}		
3	Lithium, Li	$\mu g\ l^{-1}$	Pre-fire	6	0.141	0.001	21	0.899
			Post-fire	18	0.144	0.007		
4	Molybdenum, Mo	$\mu g\ l^{-1}$	Pre-fire	28	0.076	0.0001	18	0.163
			Post-fire	19	0.105	0.007		
5	Magnesium, Mg	$mg\ l^{-1}$	Pre-fire	28	0.855	0.009	29	0.254
			Post-fire	19	0.899	0.021		
6	Strontium, Sr	$\mu g\ l^{-1}$	Pre-fire	28	2.489	0.611	33	0.012
			Post-fire	19	3.200	0.932		
7	Arsenic, As	$\mu g\ l^{-1}$	Pre-fire	27	0.052	2.00×10^{-5}	24	0.008
			Post-fire	19	0.059	8.20×10^{-5}		
8	Chloride, Cl	$mg\ l^{-1}$	Pre-fire	28	9.68	0.340	27	0.019
			Post-fire	19	10.29	0.930		

Most often, the increases in metals occurred in zone G–J, which again can be explained by the shallow groundwater table. Other elements did not show any clear changes that could be attributed to the wildfire and appeared to be unaffected by the fire. The behaviour of nutrients and other elements was analysed, revealing no changes for most major elements, although an increase is often cited in other research.[33,34] Fluoride and sulphate showed a statistically significant increase after the fire in the Braga Region in Portugal.[33] The detection limit (DL) used at the laboratory ALS Scandinavia AB for fluoride, sulphate, selenium, and boron in Heidmork was sometimes above the natural background level, so limited measurements are available for registering any change for those parameters, as shown in the ESI file.†

Hydrometeorological data

Meteorological measurements clearly show the impact of the drought on the hydrology (Fig. 4). The average precipitation in December, January and February preceding the fire was approximately half the monthly average (90 mm). This resulted in a low volumetric water content in the soil in the open field of the water intake zone at ML and an exceptionally low groundwater level in boreholes at VK. The volumetric water content in soil was low for the late winter period leading up to the fire, fell significantly at the beginning of January and did not recover to the normal stage until after the heavy rain incident on May 29th (Fig. 5). The groundwater level in borehole VK-1 was low in the first months of 2021 compared to the daily average (2008–2020) and exceptionally low in the weeks leading up to the fire (Fig. 6). These measurements demonstrate the importance of systematically monitoring the hydrometeorological parameters to provide early warning for potential wildfires.

Lessons learned for wildfire risk mitigation

Summary of the event. On May 4, 2021, a large wildfire broke out in Heidmork, the water primary protection zone for the capital, after a long period of drought. The wildfire at Heidmork lasted for eight hours. A total of 56.5 ha of land burned. The main vegetation that burned was stick pine (*Pinus contorta*), lupin (*Lupinus nootkatensis*), and old wild birch forest (*Betula pubescens*). The wildfire was less than 300 metres from the fencing of the water intake zone of VK, about 700 metres from the boreholes inside the VK zone, and three to five kilometres from the other two zones (ML and G–J) (Fig. 1). The wind was mainly south-easterly and blew the smoke in the direction of the VK zone and also towards the other two zones (G–J and ML).

Water supply. During the fire there was concern about the infrastructure and a water faucet was installed by the boreholes in the VK zone for firefighting purposes and a water tank was put on overflow for watering the surroundings. Following the wildfire various preventive measures have been implemented by the water utility to reduce the risk of fires and minimize the impact if they occur. The Veitur Utilities already had a long-standing water safety plan in place[52] though it did not include a risk assessment of wildfires, which has been added now. The lessons learned for the water sector from this incident are summarized into the following list of actions recommended:

Working group

- Establish a working group that has the responsibility to incorporate wildfires into preventive management and produce an emergency response plan in the case of a wildfire. The risk management plan should include both infrastructure improvements and regular control measures.
- The response plan should be regularly rehearsed.
- Precautions should be taken when using large equipment in the water protection areas during fire or rehearsal, due to the risk of oil pollution.

Collaboration and knowledge

- Collaborate with the local fire brigade and other stakeholders such as the local rescue team, neighbouring water supplies, landowners in the area, and the general public.

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Table 4 PAHs and Volatile Organic Compounds (VOCs) in water samples (µg l^{-1}) after the wildfire in Heidmork 4.5.2021

			Place of sampling												
			Date: 11.5.2021			Date: 25.5.21	Date: 19.10.2021			Date: 10.5.2022			Date: 18.10.2022		
Chemicals	Agency	MCL[a] µg l^{-1}	VK-1 VK	V-4 G–J	V-19 G–J	DN[b] Laxalón	V-3 G–J	V-13 ML	VK-2 VK	V-1 G–J	V-13 ML	VK-1 VK	V-23 G–J	V-5 G–J	VK-5 VK
PAHs															
Naphthalene (NAP)-2 rings	CCME[c]	7	**0.0011**	**0.0011**	**0.0012**	<0.001	<0.001	<0.001	**0.0011**	<0.007	<0.007	<0.007	<0.007	<0.007	<0.007
Phenanthrene (Phe)-3 rings	CCME	1	<0.001	<0.001	**0.0012**	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Dibenz(*ah*)anthracene (DahA)-5 rings	EPA[d]	0.3	<0.001	**0.0027**	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006	<0.0006
Benzo(*ghi*)perylene (BghiP)-6 rings	CCME	0.2	<0.001	**0.0021**	<0.001	<0.001	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
Indeno(1,2,3-*cd*) pyrene (Ind)-6 rings	CCME	0.2	<0.001	**0.0014**	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
PAH sum 16			**0.0011**	**0.0073**	**0.0024**				**0.0011**						
PAH sum carcinogenic	EU DWD[e] SUM 4	0.1		**0.0041**											
PAH sum rest			**0.0011**	**0.0032**	**0.0024**				**0.0011**						
VOCs-BTEX															
Ethylbenzene	CCME	2.4	<0.1	<0.1	<0.1	**0.21**	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Toluene	CCME	24	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	**0.5**	**0.5**	**0.5**
Xylenes SUM	CCME	72	NA[f]	NA	NA	NA	<0.15	<0.15	<0.15	<0.2	<0.2	<0.2	**0.7**	**0.8**	**0.6**
SUM BTEX						**0.21**							**1.2**	**1.3**	**1.1**
other VOCs															
Dichloromethane	EPA	5	<0.1	<0.1	<0.1	<0.1	<0.1	**0.9**	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cis-1,2-dichloroethene	CCME	1.6	**0.045**	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Tribromomethane			<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	**0.21**	<0.2
Sum VOC other			**0.045**					**0.9**						**0.21**	

[a] MCL = maximum contamination level. [b] DN = distribution network. [c] CCME = Canadian Council of Ministers of the Environment guidelines for shallow soils under potable groundwater conditions. [d] EPA = Environmental Protection Agency, USA. [e] EU-DWD = EU Drinking Water Directive (EC 2184/2020) SUM 4 PAHs (benzo(*b*)fluoranthene, benzo(*k*)fluoranthene, benzo(*ghi*) perylene, and indeno(1,2,3-*cd*) pyrene). [f] NA = not analysed.

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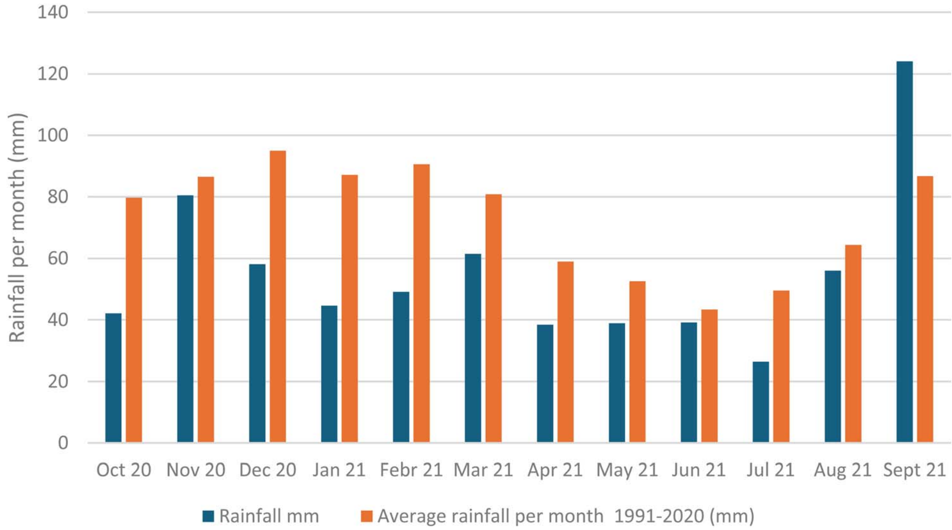

Fig. 4 Monthly rainfall in Reykjavik from 1.10.2020 to 1.10.2021 compared to the average monthly rainfall for the period 1991–2020.

Fig. 5 Volumetric water content in soil in pine forest (green) and open field (brown) from 1.10.2020 to 1.10.2021 measured in the water protection area ML. The vertical line shows the timing of the wildfire.

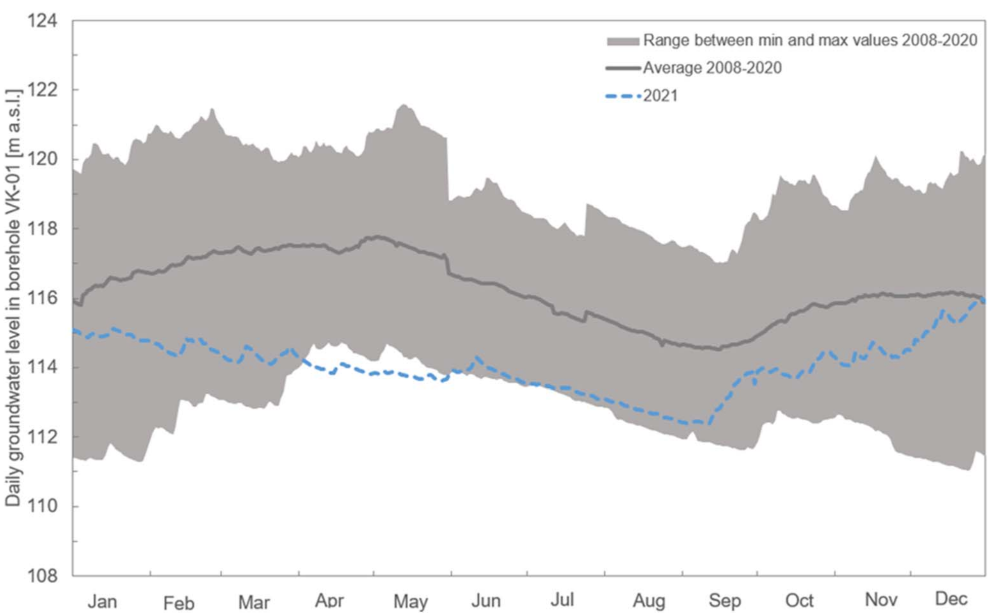

Fig. 6 Average groundwater level for VK-1 for the period 2008–2020, where the shaded area shows the range of the max mean values. The blue line shows the level for 2021.

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- Increase knowledge and research on the impact of wildfires on water supply, water quality and the natural environment.
- Work with authorities and stakeholders to restrict land use in watersheds, *e.g.* forestry and open fire.

Improvements of infrastructure

- Replace wooden structures with fire-resistant building materials.
- Create a buffer zone around the area.
- Install water faucets and fire claps for firefighting at critical locations.
- Clear vegetation around infrastructure and replace soil with gravel.
- Build access roads for firefighting that can also be used as escape roads.
- Invest in suitable equipment and spare parts for preparedness, *e.g.* electrical equipment.

Regular control measures

- Vegetation management by clearing vegetation away from infrastructure and replace soil with gravel on a regular basis.
- Monitor available hydrometeorological data to use in risk management.
- Regular patrols when a warning of wildfires is issued.
- Develop a sampling plan to monitor water quality following a wildfire to register infiltration of contaminants into groundwater.

Local fire brigade. The fire in Heidmork is among the larger incidents the Metropolitan Fire Department Fire Brigade has worked on. During the incident, assistance was needed from neighbouring fire brigades, both in staff and equipment and *ca.* 150 people participated in the firefight. Since the fire, the fire brigade has invested in additional firefighting equipment. A standard procedure is to use only water for firefighting in water protection areas, as in this case, fire foam is ecotoxic. It was difficult to travel around the area during the fire. This has also been the case for extinguishing wildfires in lava fields during the recent volcanic eruptions in the Reykjanes peninsula.

The lessons learned for the fire brigades from this incident can be summarized into the following list of actions recommended:

- Secure collaboration and dialog between stakeholders.
- Increase knowledge and increase public awareness of the vulnerability of water sources.
- Update and rehearse the emergency plan in cooperation with stakeholders.
- Restrict access to protection zones for water supplies as most wildfires are man-made, *e.g.*, from open fires, grilling, or smoking.
- Ensure access for firefighting and patrolling as part of regional land planning.
- Staffing and equipment must be secured for large incidents.
- Survey weather related data and warn the municipalities and the public of potential risks.
- Restrict forestry in the watershed as it provides fuel for fires, especially pine trees, as the pine needles contain resin, which is fuel for fire.

The lessons learned from this wildfire are very similar to those depicted in Sham *et al.*[53] from a survey among 27 water supplies in the US, mentioned earlier, supporting the universal actions recommended here.

Conclusions

Climate change in Iceland is expected to lead to higher air temperatures and more intense precipitation and also longer and more intense drought periods.[40] The consequences are increased growth in vegetation, grass, shrubs and trees. This leads to overgrowth that can fuel large fires during drought periods. This study evaluates the impact of a large wildfire that took place on May 4, 2021, on the water source for the capital area of Iceland, using results from regular audit monitoring from boreholes in the vicinity of the burned area. The main contaminants detected were PAHs and VOCs including BTEX, while some metals were found at concentrations two to sixfold higher than their median values before the wildfire.

The analysis shows that even though this fire incident in Heidmork did not permanently contaminate the aquifer and the parametric values were not exceeded, aquifers are vulnerable to wildfires, especially to PAHs, VOCs and other chemicals. This is especially the case in porous postglacial lava fields like Heidmork and it is essential to analyse the vulnerability and develop an appropriate emergency preparedness plan. Further research is recommended on the impact on water quality from wildfires on other contaminants, such as metals or nutrients spanning longer periods before and after the fire.

The lessons learned are that it is important to have a thorough emergency response plan in place built on risk assessment of the impact of wildfires on drinking water quality. The plan must be tested and it is important to start a special monitoring programme immediately in the case of wildfires and should be adapted to precipitation events during the period and continue for at least a year. A vegetation maintenance plan should be put in place to limit growth and provide access to areas, in addition to adding necessary fire-resistant infrastructure. It is important to develop a long-term plan to protect the groundwater in Heidmork that considers the natural changes that will take place due to climate warming forcing, as the Heidmork area is the most important water resource in Iceland, serving 64% of the population of the country. The lessons learned from this fire incident can be applied to the water sector in Iceland and elsewhere.

Data availability

According to regulations, all water quality data are available for the public on request and all data used in this paper can be obtained from Reykjavik Energy.

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Conflicts of interest

There are no conflicts of interest to declare.

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