QJEGH

Research article

Quarterly Journal of Engineering Geology and Hydrogeology

https://doi.org/10.1144/qjegh2021-078 | Vol. 55 | 2022 | qjegh2021-078

Revealing the importance of groundwater for potable private supplies in Wales

G. Farr[1]*, E. L. Ander[2], K. James[3], A. Kibble[3], D. A. Jones[4] and C. Jones[5]

[1] British Geological Survey, Cardiff University Main Building, Park Place, Cardiff CF10 3AT, UK
[2] British Geological Survey, Keyworth, Nottingham NG12 5GG, UK
[3] Public Health Wales, 2 Capital Quarter, Tyndall Street, Cardiff CF10 4BZ, UK
[4] Natural Resources Wales, Ty Cambria, 29 Newport Road, Cardiff CF24 OTP, UK
[5] Powys County Council, Powys County Hall, Spa Road East, Llandrindod Wells LD1 5LG, UK
GF, 0000-0002-1821-3122; ELA, 0000-0003-3901-1949; AK, 0000-0002-7657-5957; DAJ, 0000-0001-5122-6884
Present addresses: GF, The Coal Authority, 200 Litchfield Lane, Mansfield, NG18 4RG, UK
* Correspondence: GarethFarr@coal.gov.uk

Abstract: At least 77 000 people across Wales rely on private water supplies for their drinking water, with 94% of these supplies dependent on groundwater. Potable private water supplies were mapped to Lower Super Output Area level, creating the first map of its kind for Wales. Some rural areas report nearly 43% of properties using private water supplies as their principal source of water. Simplifying the complex geology of Wales into 'hydrostratigraphic units' shows that 97% of private water supplies are sourced from secondary aquifers that have low productivity and storage. Ordovician and Silurian bedrock aquifers and associated Quaternary deposits support nearly 75% of all private water supplies. The total volume of groundwater abstracted by licensed and unlicensed potable private water supplies across Wales is estimated at 24.6 Ml day^{-1}. In times of drought many of Wales' low-storage aquifers can experience insufficiency events. During 2018, reports of 132 dry supplies were collated; however, we suspect that many cases were not reported. In a changing climate with more extreme weather events, and as working from home becomes more common, private water supply users in low-storage and low-permeability aquifers may find themselves at increasing risk of insufficiency events.

Thematic collection: This article is part of the Climate change and resilience in Engineering Geology and Hydrogeology collection available at: https://www.lyellcollection.org/cc/climate-change-and-resilience-in-engineering-geology-and-hydrogeology

Received 7 June 2021; **revised** 27 February 2022; **accepted** 28 February 2022

Private water supplies (pws) are used for potable drinking water, commercial, industrial, agriculture and leisure purposes, often in areas where connection to the mains public water supply is not possible. Globally these abstractions provide water to billions of people, and may increasingly be at risk of depletion as a result of pressures from climate change and abstraction demand (Jasechko and Perrone 2021). Although perhaps more recognized as water supply sources in low-income nation settings, there are considerable numbers of users in high-income nation settings as well. For example, in Europe, it was estimated that 20 million people (7% of population) use small pws, serving fewer than 50 people, in 27 nations that responded to a survey by the World Health Organization (Rickert *et al.* 2016).

There are 74 251 registered pws in Great Britain (DWI 2019; DWQR 2019) of which 14 846 potable supplies are registered in Wales. In Great Britain it is estimated that at least 1.9% of the population or about 1.27 million people use water from pws (DWI 2019; DWQR 2019). In Wales over 77 000 people are known to live or work in properties that depend upon pws (DWI 2017). Analysis of properties that do not fall within the public water mains supply area suggest that there could be as many as 41 760 pws in Wales covering potable, agriculture, tourism and commercial uses (ARUP 2021). In Britain, private water supplies can be sourced from surface waters, including rivers or lakes, rainfall collectors and groundwater sources, including boreholes, wells, adits and springs.

The majority of potable pws are unlicensed and abstract relatively small volumes of water; however, supplies that abstract more than 20 m^3 day^{-1} are licensed by Natural Resources Wales. Private water supplies to domestic properties are known to be vulnerable to water quality problems (e.g. Ander *et al.* 2016; Crabbe *et al.* 2017; DWI 2017). However, water supply vulnerabilities, and risks from future changes arising from changing climate (CCRA 2017), are often poorly understood for these types of small supplies in Great Britain. Research in the USA (Murti *et al.* 2016) illustrated that during drought events pws users had reduced their indoor and outdoor consumption.

Drought has been a recurring feature of the UK climate (Environment Agency 2006); however, pws users may face more frequent challenges from a changing climate, with extreme weather events (Murphy *et al.* 2009; CCRA 2017) often resulting in insufficiency of supply during droughts or contamination of supplies during flood events. The effects of drought on water users are rarely considered in temperate climates (Bryan *et al.* 2020). Predictions of a higher likelihood of drought (Burke *et al.* 2010) and extreme weather events (Murphy *et al.* 2009; Kendon *et al.* 2013; CCRA 2017) underline the urgent need for a better understanding of the location of pws and the resilience of the aquifers from which they abstract water in order to better protect the people and businesses who depend on them. Spatially predictive models (Mansour *et al.* 2018) also suggest future variability and change of groundwater recharge, with some areas seeing a reduction and others an increase in effective recharge to groundwater. Effects of insufficiency can be wide ranging and can include impacts on water supply, water quality and agriculture (e.g. Cook *et al.* 2017), and on physical and mental well-being (Welsh Government 2015), and financial and operational challenges for businesses and home owners. It is possible that insufficiency events will have a greater impact on the elderly, less mobile or otherwise more vulnerable in society. During the COVID-19 pandemic, which saw several lockdowns and many people working from home from mid-March 2020, water use in some areas was noted to have increased by 25% as a combined effect of warm temperatures and people being at home more often (Water UK 2020). If the move to working from home or relocating to more rural areas becomes more common it is possible that water demand from potable pws could increase.

One challenge to better understanding risks to pws is the absence of publicly available maps describing the location and source of pws at a resolution below that of local authority. This lack of mapping can result in difficulties for local authorities, water companies, government bodies, environmental regulators, planners and developers, who all require information about the location to protect pws and their users. To compound this issue no official records of pws affected by resilience issues (drought) in Wales have historically been collated.

This paper aims to improve the understanding of the location and source of potable pws abstracting from groundwater across Wales, to reveal where these are important in order to underpin management of future drought-induced insufficiency events, including the potential effects of longer-term water stress owing to climate change. The first Wales-wide map of pws distribution, estimated abstraction volumes and occurrences of insufficiency following the 2018 drought (Turner *et al.* 2021) is presented. The importance of groundwater for pws in Wales is described and supplies are attributed to 'hydrostratigraphic units', which are geological units with similar hydrogeological characteristics or properties (Loveless *et al.* 2019).

Study area

Wales had an estimated 1.3 million households and a population of 3 125 200 in 2107 (ONS 2017). Wales covers an area of 20 700 km^2 of which 80% is used for agriculture (Welsh Government 2019) and is both topographically and geologically varied. The population is concentrated in coastal cities in the south and in larger towns along the coast in the north and west. Inland, a significant population was established in the south Wales valleys during the development of the extractive coal industry. The interior is mountainous, rural and sparsely populated. Annual rainfall can vary from 3000 mm a^{-1} in Snowdonia to 1000 mm a^{-1} along the coast (Met Office 2021).

Private water supplies provide water to about 77 000 people across Wales from 14 846 registered supplies (DWI 2019). Environmental health officers at 22 local authorities are responsible for recording, risk assessing and testing the water quality of pws in line with the requirements of The Private Water Supply (Wales) Regulations (2017). The majority of pws (81%) are classified as 'single domestic dwellings' and are often the only water supply to rural and remote properties, many of which cannot access the mains water supply network.

The majority of Welsh aquifers are considered to be of low to medium productivity and as such are classified as 'secondary A or B aquifers', previously known as minor aquifers and non-aquifers respectively (Jones *et al.* 2000). Secondary aquifers cover 94.7% of Wales' surface area and are considered important for pws; however, they can have relatively poor aquifer properties (e.g. moderate to low productivity and storage capacity). Groundwater in bedrock aquifers, contained mainly within shallow weathered zones, joints and fractures, generally supports small localized supplies. Quaternary sand and gravel aquifers classified as 'secondary A' aquifers are also used for smaller localized public water supplies (e.g. Hiscock and Paci 2000). Groundwater for public supply in Wales is abstracted mainly from the principal Carboniferous Limestone and Permo-Triassic sandstone aquifers (Allen *et al.* 1997); however, principal aquifers cover only about 5.3% of Wales' surface area, in the far NE and south of the country.

Hydrogeological information for aquifers that support pws in Wales is limited (Neal *et al.* 1997; Robins 1999; Hiscock and Paci 2000; Jones *et al.* 2000; Robins *et al.* 2000, 2007; Moreau *et al.* 2004; Robins and McKenzie 2005; Shand *et al.* 2005; Jones and Farr 2015; Robins and Davies 2016) and as a result there is a paucity of data for many of these secondary aquifers and their response to drought is poorly understood. A review of historical drought in rural communities in Wales provides evidence that insufficiency of supply in Wales is not a new occurrence, despite it often being considered a 'wet' country (Waddington 2017). However, since the nineteenth century resilience to drought stress has improved (Marsh *et al.* 2007), possibly owing to advances in mitigation, planning and infrastructure (EA 2006).

Methods

Private water supply data

Private water supply records are maintained by local authorities, and compiled annually into a national dataset by the Drinking Water Inspectorate (DWI). The DWI supplied the pws records for 2015 with their location aggregated to Lower Super Output Areas (LSOAs) (DWI 2017; Ander *et al.* 2020). The LSOAs are geographical delineations, fully nested within other administrative geographies, including that of local authority (ONS 2011), suitable for provision of consistent spatially referenced data. The LSOAs represent areas that contain between 400 and 1200 households or 1000–3000 people, and there were 1909 LSOAs in Wales in the Census 2011. This spatial aggregation therefore ensured that the location of individual supplies, or households, remained confidential during this study in accordance with data protection regulations and best practice. Further data checks established that 473 pws had not had location records updated for legacy reasons and these had been recorded to the local authority office LSOA. These were removed from further analysis to avoid skewing results. It is acknowledged that there are potentially many unreported pws across Wales, particularly those likely to be used for single domestic dwellings; however, only the official records were used as no other data were available from which to estimate the number of missing sites. Non-potable abstractions for agriculture (e.g. irrigation and livestock watering) or small-scale industrial processes were also excluded.

The Private Water Supply (Wales) Regulations (2010), in force for the reported data from 2015, categorized supplies into single domestic dwellings (no regulation number), small shared supplies (Regulation 10), large supplies (Regulation 9) and redistribution networks (Regulation 8), and this terminology is used in this paper. Subsequent changes to the Welsh Regulations (The Private Water Supply (Wales) Regulations 2017) mean that later data are recorded as redistribution networks (Regulation 8), large supplies (Regulation 9), single domestic dwellings (Regulation 10) and small shared supplies (Regulation 11). 'Supplies' is used specifically to refer to the water sources at point of abstraction, not the properties or households estimated to be using the supplies, which will be larger in number.

The sources of pws in Wales (DWI 2017) were simplified into three categories: (1) groundwater, including springs (SPW), wells (WEL), boreholes (BHW) and adits, and mixed sources (MMS; MXW); (2) surface water (SFW) including streams, ponds and lakes; (3) rainwater (RNW) including rooftop and other catchment systems. Missing source data are recorded as unknown (UNK).

Delineating hydrostratigraphic units

The bedrock and Quaternary geology of Wales is complex, and a simplified classification was required to support a broad Wales-wide analysis of pws sources. The framework used was that of ‘hydrostratigraphic units’ defined as geological formations, or groups of formations, with similar hydrogeological characteristics or properties (e.g. porosity or hydraulic conductivity) relating to groundwater flow, and potentially other hydrogeological characteristics, such as groundwater chemistry (Loveless *et al.* 2019).

Bedrock

The hydrostratigraphic units aquifer map was derived from the British Geological Survey’s 1:625 000 scale bedrock geology dataset (Loveless *et al.* 2019). Ten hydrostratigraphic units were created: Precambrian; Cambrian; Ordovician and Silurian; Devonian; Carboniferous Limestone; Carboniferous Coal Measures; Permo-Triassic sandstones; Triassic Mercia Mudstone; Jurassic (Lias); Eocene. For the purposes of aquifer management, the Carboniferous Limestone and Permo-Triassic sandstone are classified as principal aquifers (whereas the remaining geologies are classified as secondary A or B aquifers (Jones *et al.* 2000).

Quaternary

Quaternary aquifers were mapped using the British Geological Survey’s 1:625 000 scale superficial deposits productivity map developed by Coxon *et al.* (2020). Hydrogeological classes for each formation type were derived based upon information on their relative productivity, primary hydrogeological data and dominant lithology. Coxon *et al.* (2020) divided the Quaternary deposits into five classes; however, for this analysis the classes were simplified into two groups: ‘moderately productive Quaternary deposits’ (including glacio-fluvial and alluvial sand and gravel deposits) and ‘all other Quaternary deposits’ (including peat, diamicton (till), blown sands and mudflat deposits), which are considered to be less productive water sources.

Estimating abstraction volumes

The volume of water abstraction for the majority of unlicensed pws is not recorded, so a method of estimating this was developed. Private water supply numbers and types (DWI 2017) were assigned estimated abstraction volumes. Single domestic dwellings were estimated assuming a daily usage of 150 l per person (Environment Agency 2009) and an average occupancy of 2.3 people per property (Office for National Statistics Average Household Size Wales; 1991–2019). Large pws (Regulation 9) are defined partly on the basis of a minimum abstraction of 10 m^3 day^{-1}. The number of households using each small shared supply is not recorded, so a value of 5 m^3 day^{-1} (half of the maximum permissible small shared volume) was attributed to each supply. The data for redistribution networks (Regulation 8) were not used as these were assumed to refer to the onward supply of public water supplies. For supplies greater than 20 m^3 day^{-1} an abstraction licence is required and abstraction data were supplied by Natural Resources Wales for 66 licensed private water supplies, comprising 24 surface water abstractions and 42 groundwater abstractions. The daily authorized abstraction quantity for each supply was used to calculate a total for licensed potable pws in Wales, which was added to the estimated volume of unlicensed pws described above.

Spatial data integration and analysis

ArcGIS (v10.3, ESRI) was used for geographical analysis and map production. Spatial joins were used to link the LSOAs and the hydrostratigraphic units, with the percentage of each hydrostratigraphical unit in each LSOA calculated. For the majority of LSOAs only one hydrostratigraphic unit was present; however, where the LSOA polygon intersected more than one hydrostratigraphic unit polygon, the pws were allocated pro rata to the relative areas of the aquifers, because location information within the LSOAs was not available.

Reports of insufficiency during 2018

Failed (dry) pws were voluntarily reported by householders to each local authority and then collated by the Welsh Government. There was no methodical survey to assess the type or location of supplies affected by drought. Only potable pws were reported; agricultural supplies were not included. To protect users’ data they were aggregated at a local authority scale. A total of 132 cases of insufficiency in potable pws were collated by the Welsh Government during 2018, with the first recorded during the week commencing 16 July and the last in the week commencing 3 September. Although this study focuses on Wales it is worth noting that similar issues were experienced elsewhere in the UK (e.g. in Scotland; Rivington *et al.* 2020) and in the Republic of Ireland (Mooney *et al.* 2021).

Results

Of the 14 846 registered pws in Wales, the 94% that were sourced from groundwater (boreholes, wells, springs and adits) were used, equating to 13 657 supplies.

Spatial mapping of potable private water supplies

The first national maps showing the spatial distribution of potable pws disaggregated within local authority areas are presented (Figs 1 and 2). These maps show considerable variation in number of records and estimated proportion of households, even within the authority areas with the largest number of supplies. They also suggest boundary effects between the different authority areas (e.g. boundary of Gwynedd and Powys), which are probably due to differences in reporting. The smaller, urban local authority areas show a low density of pws, as most properties are supplied by mains water, especially in south Wales and along the north Wales coast. Higher numbers and percentages of pws are recorded in mid, west and north Wales where populations are more rural and dispersed. Of these, Powys covers the largest area in Wales, has the most recorded pws, and also contains the highest number of pws in a single LSOA with 415 pws (Fig. 1), which equates to 43% of the known properties in the area (Fig. 2).

Allocation of supplies to hydrostratographic units

Hydrostratigraphic units for bedrock and Quaternary aquifers (Fig. 3) were derived from 1:625 000 British Geological Survey data. The pws database does not include borehole lithological logs (recorded at the time of drilling), or if they are well or spring sources, thus it was not possible to identify if the source of groundwater was from the Quaternary or bedrock aquifers or a mixture of both. Unique bedrock hydrostratigraphic units were delineated for 67% of the LSOAs. Greater discrepancy was found in other areas, especially for coastal LSOAs, which are mapped down to the mean low tide level, and thus include estuaries, coastal blown sands and beaches that are not expected to form potable pws aquifers to any great extent.

The hydrostratigraphic units approach also allows us to make a first estimate of the importance of groundwater abstraction (via springs, wells or boreholes) from formations that have previously been considered to hold inconsequential quantities of water. Table 1 shows the distribution of groundwater-sourced pws attributed to hydrostratigraphic units. It is found that 97% of pws are estimated to be sourced from areas that are traditionally considered to be poorly

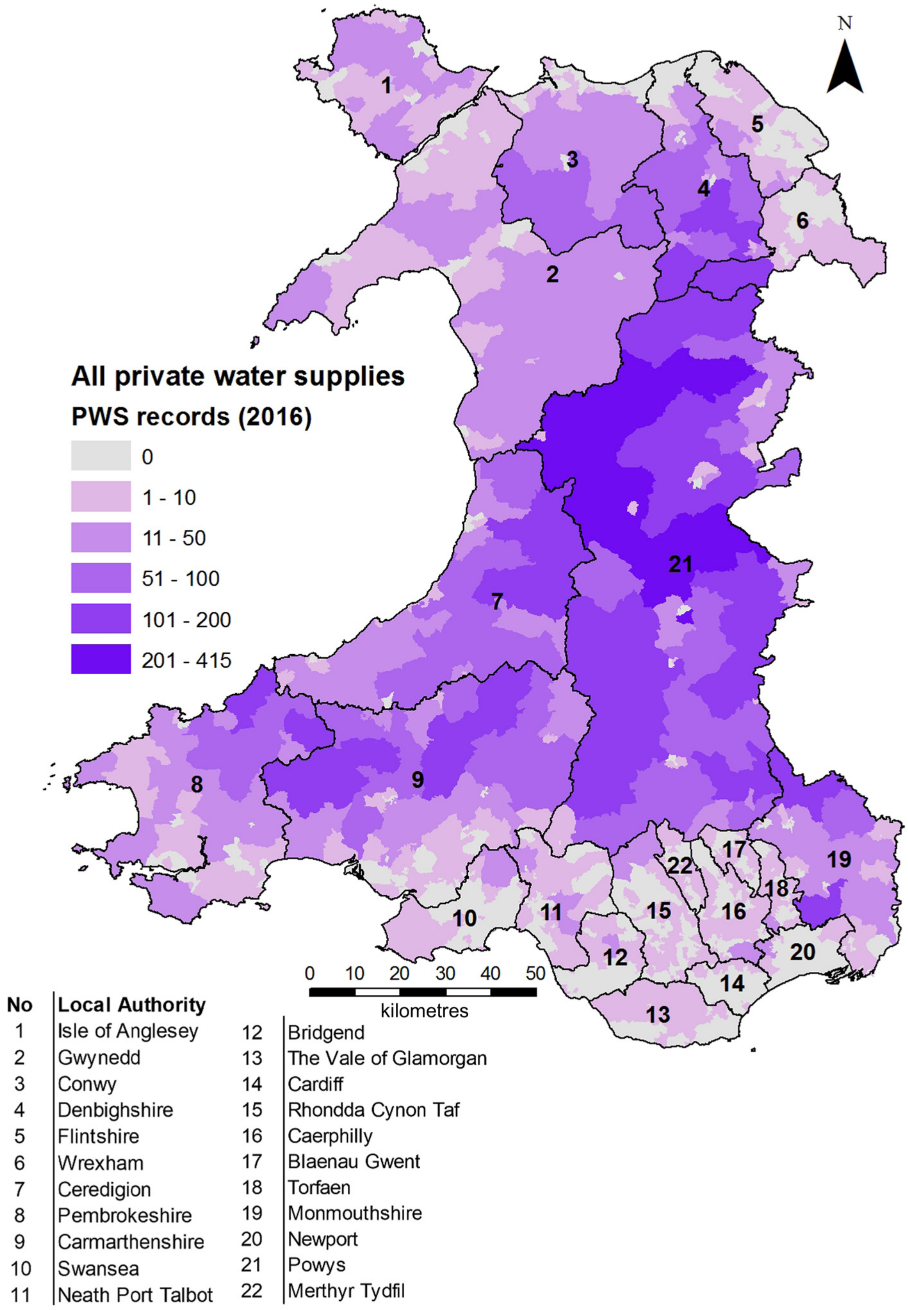

Fig. 1. Total number of private water supplies in Wales per Lower Super Output Area (LSOA). Contains Ordnance Survey data licence number [100021290 EUL] © Crown Copyright and database rights 2021. Mapping to LSOAs spatial data, ONS (2011) used under Open Government Licence (OGL). Private water supply data aggregated to LSOAs used with permission of Drinking Water Inspectorate.

productive ‘secondary’ bedrock aquifers whereas just 3% are sourced in areas underlain by principal aquifers (Permo-Triassic and Carboniferous Limestone).

Cambrian and Precambrian bedrock hydrostratigraphic units and associated Quaternary deposits support an estimated 2% ($n = 281$) of potable pws in Anglesey, Pembrokeshire and Gwynedd. These units often contain groundwater in fractures and fissures close to the surface with short flow paths on a local catchment scale (Robins and McKenzie 2005).

Ordovician and Silurian bedrock aquifers and associated Quaternary deposits are the most geographically widespread hydrostratigraphic units, covering 57% of Wales’ land surface, and are estimated to support 75% ($n = 10\,297$ supplies) of all groundwater-supported pws. Ordovician and Silurian strata are considered to be poor aquifers in a UK context (e.g. Jones *et al.* 2000), and very little is known about their properties for water storage or how they respond to drought events.

Devonian bedrock aquifers and associated Quaternary deposits are estimated to support 13% ($n = 1819$) of potable pws in Wales, largely in Monmouthshire and Powys. Devonian aquifers are locally important, supporting many private and licensed groundwater supplies for potable, agricultural and industrial use (Moreau *et al.* 2004; Robins and Davies 2016).

Carboniferous Limestone bedrock hydrostratigraphic units and associated Quaternary deposits are estimated to support 2% ($n = 274$) of potable pws. The Carboniferous Limestone is classified as a principal aquifer and can have significant secondary permeability via karstic features, fractures, bedding planes and solution features (Allen *et al.* 1997), and is capable of supporting large public and private water supplies. However, drilling into limestone can be unpredictable and if water-bearing features are not intercepted boreholes can be dry.

Carboniferous Coal Measures, Marros Group and associated Quaternary deposits are estimated to support 6% ($n = 809$) of pws despite underlying 15% of the land area, largely in south and NE Wales. The low number of pws may be in part related to the coverage of the mains network, which services most populations on the coalfields, but also the relatively low yields of springs and

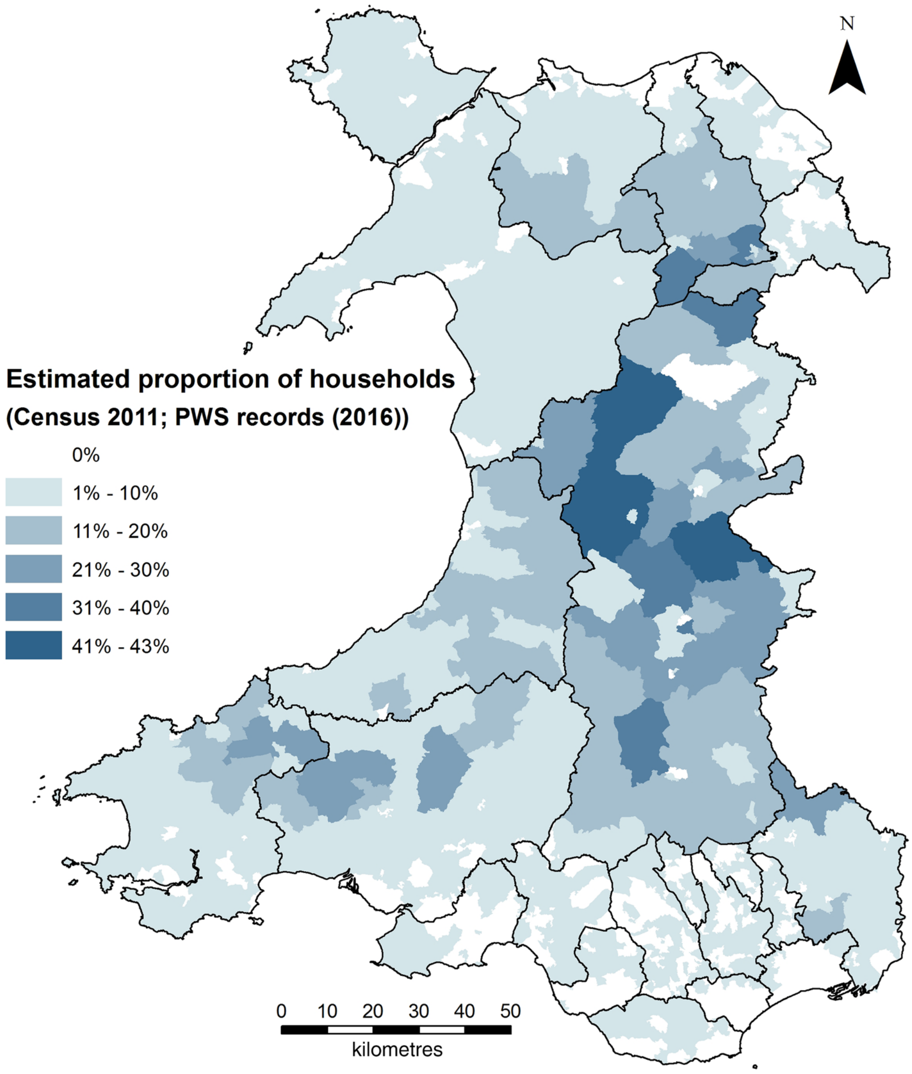

Fig. 2. Percentage of properties with a private water supply per Lower Super Output Area (LSOA). Contains Ordnance Survey data licence number [100021290 EUL] © Crown Copyright and database rights 2021. Mapping to LSOAs spatial data, ONS (2011) used under Open Government Licence (OGL). Private water supply data with permission of Drinking Water Inspectorate.

boreholes in this unit. Extensive subsurface coal mining has also resulted in large areas of the Carboniferous Coal Measures unit containing unpotable water, much of which is stored in the subsurface abandoned workings.

Permo-Triassic sandstones bedrock hydrostratigraphic units and associated Quaternary deposits are estimated to support 1% (n = 139) of all potable pws. The Permo-Triassic sandstones occur only in NE Wales and are classified as a principal aquifer. Boreholes can have an average yield of *c.* 3000 m^3 day^{-1} and artesian heads over 6 m are recorded; porosity is moderate from 19 to 31% (Allen *et al.* 1997). The Permo-Triassic hydrostratigraphic unit supports public and private water supplies, and a river augmentation scheme in the Clwyd Valley.

Jurassic Lias bedrock hydrostratigraphic units and associated Quaternary deposits are estimated to support just 0.08% (n = 10) of potable pws. The Jurassic strata occur only in south Wales and are classed as a secondary aquifer. There are very limited data on this formation, which has a low intergranular permeability with most groundwater flow via fractures or between contrasting lithologies; for example, where there are alternating limestones and shales (Jones *et al.* 2000).

Triassic Mercia Mudstone bedrock hydrostratigraphic units and associated Quaternary deposits are estimated to support just 0.19% (n = 26) of potable pws. The Mercia Mudstone occurs mainly in south Wales, underlying the cities of Cardiff and Newport, and is classified as a secondary aquifer. Although these hydrostratigraphic units are traditionally regarded as impermeable and at best a poor aquifer, groundwater can be abstracted from occasional sandstones and siltstones that can provide localized water supplies (Jones *et al.* 2000). The marginal facies, found at the base of this group, can also yield usable quantities of groundwater.

Abstraction volume of potable private water supplies in Wales

The abstraction volumes for the majority of the unlicensed pws (Table 2) are at best estimates, as unlike the licensed abstractions monitoring is not required. When broken down into percentages based on the water source the unlicensed private water supply data show that groundwater accounts for 94% of recorded supplies, surface water for 6% and rainwater for <0.5%. Interestingly, this is almost the reverse of the public water supply, which is provided by surface water (94%), with just a small groundwater (6%) contribution.

Unlicensed potable pws abstractions are estimated to supply 23.7 Ml day^{-1} (groundwater), 1.6 Ml day^{-1} (surface water) and 0.05 Ml day^{-1} (rainwater) whereas licensed potable pws abstractions supply 0.9 Ml day^{-1} (groundwater) and 1.2 Ml day^{-1} (surface water). Combining the licensed and unlicensed data the total volume of potable pws is estimated at 27.5 Ml day^{-1}, comprising 24.6 Ml day^{-1} from groundwater, 2.8 Ml day^{-1} from surface water and 0.1 Ml day^{-1} from rainfall (Table 2).

Groundwater abstraction for public water supply is calculated from licensed volumes at 25.7 Ml day^{-1}, broadly similar to the

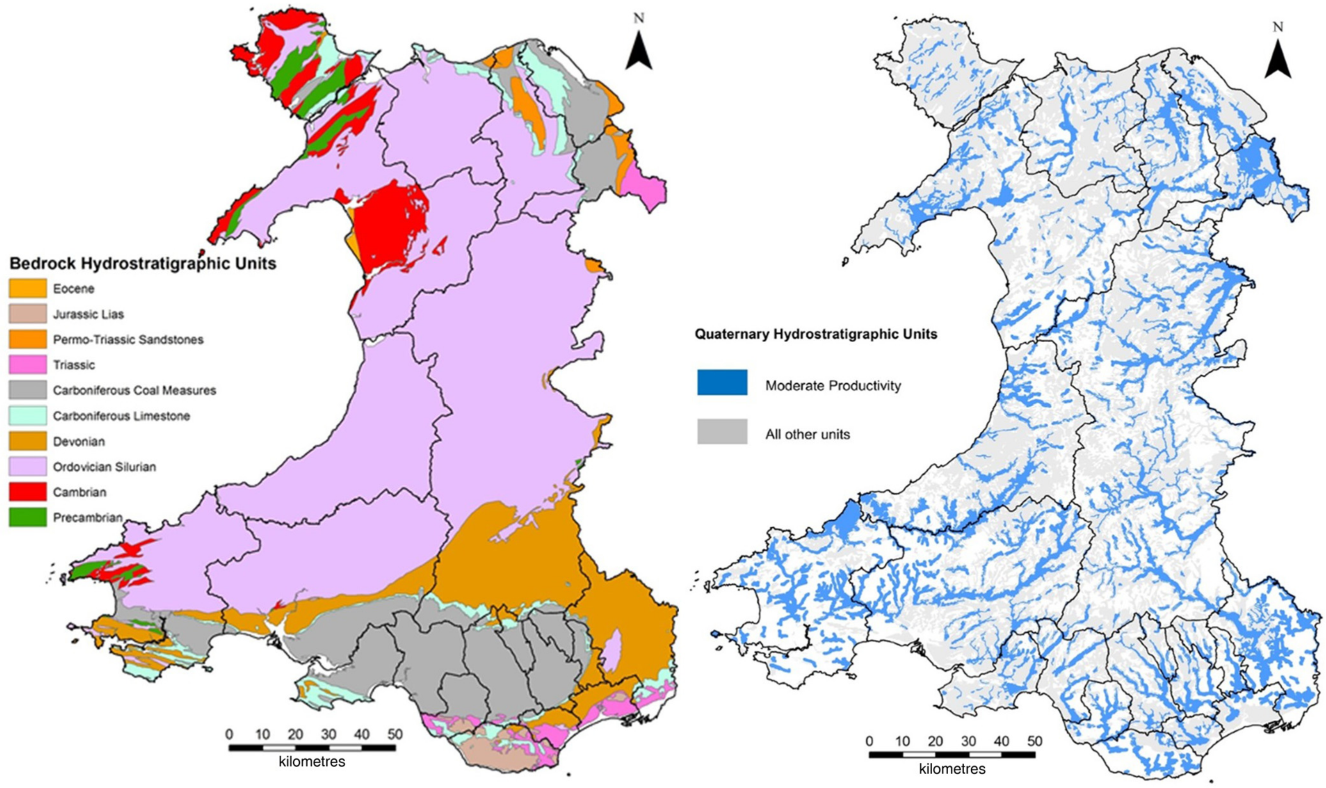

Fig. 3. Simplified hydrostratigraphic bedrock units and simplified Quaternary hydrostratigraphic units (based on relative productivity). Contains Ordnance Survey data licence number [100021290 EUL] © Crown Copyright and database rights 2021. Contains British Geological Survey 625 000 DigiMap Data V5 (2008).

estimated volume of groundwater abstraction for pws. Combining groundwater abstraction by both potable private and public water supplies it is estimated that Welsh aquifers contribute 50.3 Ml day^{-1} to Wales' potable water supply.

Dry private water supplies during the 2018 drought

Summer 2018 was dominated by dry and sunny weather from May to early August and it was the joint hottest summer on record (McCarthy *et al.* 2019). Large areas of Wales received less than 70% of average rainfall, with some areas receiving less than 50%, as a percentage of the 1981–2010 average (Met Office 2018). Local authorities recorded a total of 132 failures of supply, which is shown in the first map of reported dry pws for Wales (Fig. 4). This is likely to be a significant under-reporting of the true number of pws that had supply issues in 2018; however, there is only anecdotal evidence for this and as such the true number of supplies affected cannot be quantified.

The highest number of reports came from Gwynedd ($n = 31$), Powys ($n = 21$), Ceredigion ($n = 25$) and Carmarthenshire ($n = 22$),

Table 1. *Estimated number of unlicensed groundwater-supported private water supplies in Wales attributed to hydrostratigraphic units*

Hydrostratigraphic unit*	Aquifer classification	Surface area (km^2)	Percentage of Wales surface area (%)	Estimated number of groundwater-supported private water supplies per hydrostratigraphic unit (n)	Estimated number of groundwater-supported private water supplies (n km^{-2})	Supplies on each hydrostratigraphic unit (%)
Eocene	Sa	25	0.1	2	0.08	0.01
Jurassic Lias	Sb	228	1.1	10	0.04	0.08
Triassic Mercia Mudstone	Sb	386	1.9	26	0.07	0.19
Permo-Triassic sandstones	*P*	249	1.2	139	0.56	1.02
Carboniferous Coal Measures	Sa	3069	14.8	809	0.26	5.93
Carboniferous Limestone	*P*	854	4.1	274	0.32	2.00
Devonian	Sa	2727	13.2	1819	0.67	13.32
Ordovician–Silurian	Sa, Sb	**11845**	57.1	**10297**	0.87	75.39
Cambrian	Sb	1028	5	208	0.20	1.52
Precambrian	Sb	326	1.6	73	0.22	0.54

Total number of recorded private water supplies used in this analysis is 13 657, which represents the 96% that are sourced from groundwater from a total 14 627 reported supplies (DWI 2017). Licensed private water supplies are not included as their location data are sensitive. *P*, principal squifer; Sa, secondary A aquifer; Sb, secondary B aquifer. *Each hydrostratigraphic unit includes the associated superficial deposits in the area.

which are supported by secondary aquifers. Despite a large number of supplies there were no recorded reports of insufficiency in Anglesey or Denbighshire. It is not possible to draw significant conclusions from the reporting of failed supplies during 2018, and thus the true number of pws at risk or the most vulnerable aquifers is poorly understood.

Discussion

The spatial distribution of private water supplies

Presentation of the disaggregated location of pws shows that there is considerable variation in the location of supplies within the local authority areas, and this provides considerably more information at the national scale than the previously available local authority summaries. In particular, these data help to better understand where there may be communities with large numbers of households at risk from water supply challenges, including insufficiency, and support national contingency planning by providing a more nuanced perspective on where particular clusters of households and/or businesses may be found. There are few other examples of this level of disaggregation in the literature, with an equivalent output over a much larger area produced for the USA (Johnson and Belitz 2017).

Spatial controls are likely to include distance to mains networks in the lowest population density areas, as seen elsewhere (Johnson and Belitz 2017). Customers are responsible for all costs associated with connection and maintenance of pipework from the mains pipe, which tends to lead to a decrease in connections as distance increases, and this is why some of the most rural areas of Wales are effectively without mains supply. This new systematic national presentation of the location of pws facilitates communication of information related to aquifer properties, which inevitably cross administrative boundaries, and provides an overview of where communities, residences and businesses vulnerable to insufficiency of water supply are located.

The known absence of some pws sources in the official records, especially for the smallest supplies, is for legacy and resourcing reasons. This means that the disaggregated mapping and derived estimates are likely to improve with time as the sources of pws are recorded in line with The Private Water Supply (Wales) Regulations (2017), Schedule 5, Regulation 16.

Using the aggregated approach and reporting to an LSOA it was not possible to distinguish whether individual pws source groundwater from bedrock or Quaternary units, or both, with a high level of confidence. Future analysis could be improved by using the precise location of the pws, although this will still require some assumptions to identify the source aquifer.

The hydrostratigraphic units approach

The hydrostratigraphic units approach provides a framework for communication of the geological context of groundwater-dependent pws within and beyond the geological sciences community. In particular, this helps to widen the understanding that geologically related risks (quantity or quality) cross administrative boundaries, and is designed to build up the opportunity for shared learning between different organizations charged with protection of health or water resources where not all participants have a background in earth-environmental sciences. This hierarchical system also allows new information on specific formations to be readily integrated for dissemination.

Water usage estimates

Water use for the majority of unlicensed potable pws (single domestic dwellings) was calculated assuming an estimated volume per person (150 l day^{-1}) for users of public (mains) supplies in the absence of pws-specific data. This is a significant data gap, as it is not clear if users of pws use more water, perhaps because they view it as ‘free’ and ‘unlimited’, or whether they are wary of shortages and use less than typical mains users. It is acknowledged that this may not be an accurate reflection of private supply water use, especially in domestic settings.

Table 2. *Estimated abstraction volumes for potable water supply in Wales*

		Public water supplies	Private water supplies (licensed >20 m^3 day^{-1})	Private water supplies (unlicensed <20 m^3 day^{-1})
Number of people supplied; residential, work, holiday lets, recreational (potable water only)		3115000	n.a.	77167
Number of supplies		135	66	14846
Water source (%)				
	Surface water	93.6	56.8	6
	Groundwater	6.4	43.2	94
	Rainfall	0	0	<0.5
Number of people supplied by				
	Surface water	2958100	n.a.	4845
	Groundwater	156900	n.a.	72155
	Rainfall	0	n.a.	167
Volume (Ml day^{-1})				
	Surface water	477.1	1.2	1.6
	Groundwater	25.7	0.9	23.7
	Rainfall	0	0	0.05
	Total	502.8	2.1	25.35
Groundwater used for public supply				25.7 Ml day^{-1}
Groundwater used for potable private water supply (licensed and unlicensed)				24.6 Ml day^{-1}
Total groundwater used for potable public and private water supply				50.3 Ml day^{-1}

Private water supply data from DWI (2017). Volume estimates produced as described in the Methods section with pws broken down into types of supplies with all springs classed as groundwater abstractions. Licensed public water supply data from Natural Resources Wales and Welsh Water (Dwr Cymru Welsh Water 2019; Hafren Dyfrdwy 2019) water resources management plans. Water exported from the Elan Valley to England (381 Ml day^{-1}) has been deducted from the total volume of public water supply. n.a., not available.

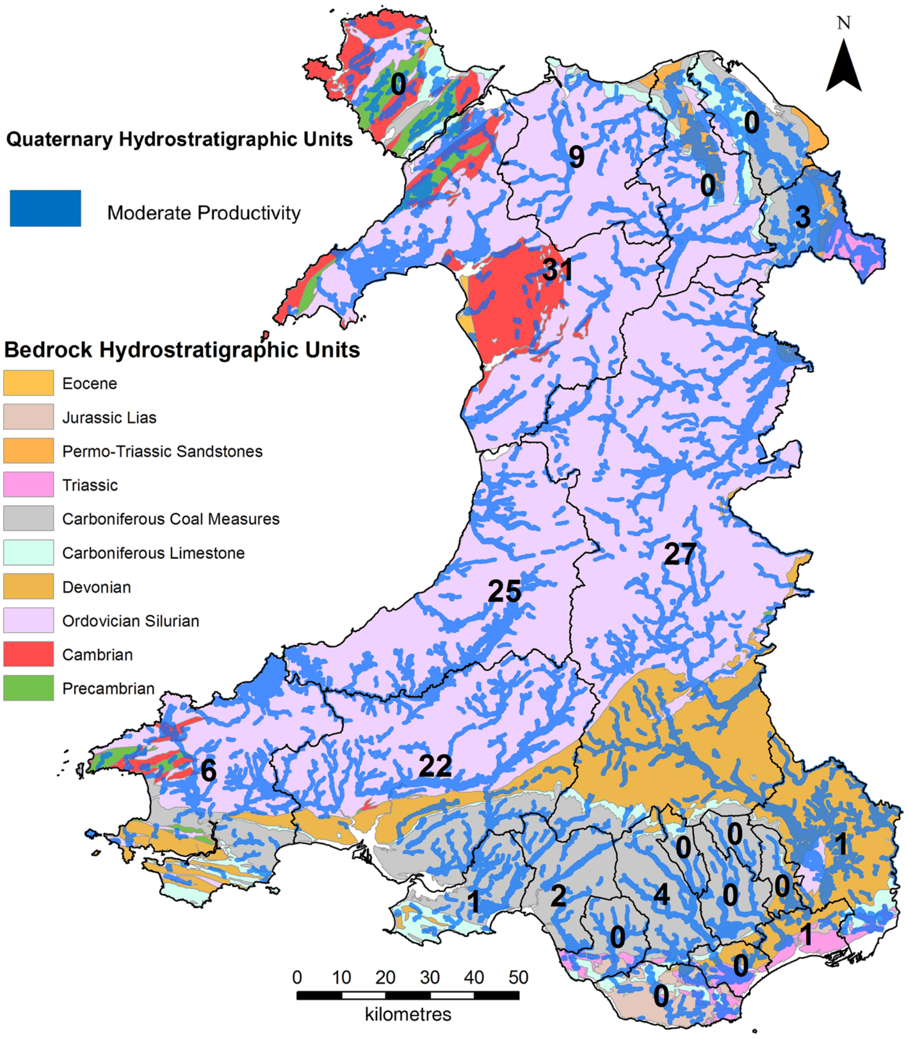

Fig. 4. Number of reported occurrences of dry private water supplies during 2018 per local authority area (black) underlain by the bedrock and Quaternary hydrostratigraphic units. Contains British Geological Survey 625 000 DigiMap Data V5 (2008). Contains Ordnance Survey data licence number [100021290 EUL] © Crown Copyright and database rights 2021. Data collated from local authorities by Welsh Government following the 2018 drought.

Robins *et al.* (2000) suggested that pws users in the Teifi Valley used on average 600 l day^{-1}; however, it was not stated if this was for potable or combined uses including agriculture. Assuming 2.3 people per household this suggests average water usage of 260 l per person per day; however, it was not possible to state how much of this was used for potable purposes or how representative this was for pws across Wales.

It is acknowledged that apart from potable water there are many other uses for private water supplies, including agriculture, leisure or drinking water for livestock. A recent estimate (ARUP 2021) suggested that there could be a total of 41 760 private water supplies with a demand of 104 Ml day^{-1} for all private water uses in Wales; however, similar data gaps on actual volumes of water used were also reported as limiting factors in this analysis.

It will be important to acquire improved water usage and availability data to better understand the resilience of the aquifers and users to low recharge or groundwater flow conditions. Given these structural uncertainties of missing data, careful thought should be given to how to control for these in any formal uncertainty calculations in the estimations of potable users, as these may be more important than the currently quantifiable parameters. Incorporation of commercial pws, such as agricultural uses, would be needed in any catchment- or aquifer-specific abstraction water balance calculations or modelling.

Current and future resilience challenges

The total numbers of reported dry pws are low compared with the number of total recorded supplies. For example, in Powys, where there are 6011 registered supplies, only 21 supplies were reported to the local authority as drying up. Although this could be taken as suggesting that the effects of the prolonged dry weather were not recognized in many aquifers, anecdotal evidence suggests that there is likely to be a significant under-reporting of drought-affected pws in Wales. Reporting in national and local media also highlighted the difficulties this creates for people whose water has run dry (BBC News Online 2018).

Under-reporting could be due to users who are ‘used to’ experiencing insufficiency of supply and have appropriate contingency plans in place (e.g. increased storage) and therefore may not report a dry water supply to the authorities. In Ireland, 32% of pws users in a survey reported experiencing the 2018 drought there. In the same survey, 27% of respondents reported using alternative water sources during extreme (drought or flooding) weather events (Mooney *et al.* 2021).

In a changing climate with more extreme weather events, pws users in low-storage and low-permeability aquifers may find themselves at increasing risk of insufficiency. Effective recharge to groundwater may increase, or decrease, or become more concentrated in shorter periods in the future (Mansour *et al.* 2018), which would affect water resource within many of the shallow fractured aquifer in Wales. This may not be recognized by pws users themselves; in Ireland 54% of study participants recognized climate change impacts as a concern for their pws groundwater quality (Mooney *et al.* 2021).

The challenges to water users may be in part due to geography (e.g. distance from an alternative supply of water) or due to difficulties or expense of a mains connection, but also due to the physical properties of the hydrostratigraphic units, many of which are unable to store large volumes of water. On-site storage tanks and other physical measures can help build resilience for pws users; however, even these systems can be limited especially after prolonged dry weather events. Dependence upon secondary aquifers, of which very little is known in Wales, compounds the risk of predicting when insufficiency events will occur and highlights the need for strategic monitoring and reporting of the status of secondary aquifer systems across Wales. The same knowledge gaps exist elsewhere in the UK where there are large numbers of private water supplies; although local water quality studies may provide specific insights (e.g. Ander *et al.* 2016), the 'desk-based' approach used here can help provide a framework in which to place localized studies (via the hydrostratigraphic unit classification), and provide a basis for galvanizing future data collection priorities in these dispersed rural settings.

There are multiple challenges that could compound resilience issues for pws users in Wales. Changing climate with drier summers and more intense rainfall could result in more frequent insufficiency events (CCRA 2017), and floods could also pollute poorly protected pws. Changing rural economies and farming practices could see water demand increase. Recently the COVID-19 pandemic has seen a move to people working from home, using an estimated 25% more water (Water UK 2020). As remote technology improves it is unknown if this will result in more people moving to, and working from home in, rural areas. If it does the demand on pws could increase.

The most numerous supplies are single domestic dwellings and metering of a small subset of these supplies could be used to understand water usage and behaviour before, during and after insufficiency events. Voluntary reporting of insufficiency events is unlikely to provide sufficient detail from which to make decisions, and it is recommended that following future drought events pws users are questioned as to the type and resilience of their supplies.

Quantifying drought response in Welsh aquifers

Traditionally groundwater resources in Wales have been considered to be poor and of little use for water supply. As a consequence there has been limited work on the hydrogeology of many Welsh aquifers. However, it is exactly because of their poor aquifer properties that they are more vulnerable to drought. Vulnerability to drought in secondary bedrock aquifers, which cover 94.7% of Wales' surface area, may be greater than in principal aquifers (Permo-Triassic sandstone and Carboniferous Limestone) owing to a lesser ability to store water. Despite this, groundwater monitoring and research in Wales has focused on the more productive principal aquifers. The few studies conducted elsewhere would appear to corroborate that drought, and an associated lack of supply, is less considered than aspects of water quality in management strategies of pws users (Murti *et al.* 2016; Mooney *et al.* 2021). Drought is perhaps also less considered in water supply terms in a 'wet' nation such as Wales (Waddington 2017; Bryan *et al.* 2020), which may have contributed to the lower priority given to research in this context. At a household level, demographic factors may also influence user actions, as seen in pws flooding and water quality research (e.g. McDowell *et al.* 2020), and should be considered in future studies alongside hydrogeological and infrastructure assessments. Data from across Europe show the importance of groundwater for many small and larger pws users (Rickert *et al.* 2016), and for which climate change may similarly need to be considered in relation to users' security of supply.

To address this knowledge gap pumping test data from boreholes in secondary aquifers, including Ordovician and Silurian bedrock aquifers, should be collated and analysed, to provide a better understanding of their physical properties and response to prolonged periods without rainfall at any time of year. Hydrographs from existing Natural Resources Wales monitoring boreholes (Jones and Farr 2015) should be analysed to provide information on their response to drought events, possibly using the Standardized Drought Indices (Bloomfield and Marchant 2013). Combining this new information an early warning system for drought in Welsh aquifers could be developed, with outputs from the most reliable and informative sites included in the monthly 'Hydrological Outlook' (http://www.hydoutuk.net/), an approach that could be replicated in any location with comparable water monitoring infrastructure. However, given the separate management of groundwater pws in Wales, accessible communication of this information to individual users will be critical for it to be effective in ensuring preparedness for scarce water supply.

Conclusions

Groundwater is often considered of less importance in Wales than in some other parts of the UK because it is not the dominant source of public water supplies. However, this study has shown that groundwater, especially from secondary aquifers, is vital for supporting pws across Wales. There are also few studies in similar geographical and socio-economic settings elsewhere, indicating a wider knowledge gap.

In Wales about 94% of unlicensed potable private water supplies are sourced from groundwater (springs, wells and boreholes), 6% from surface water (rivers, streams and lakes) and <0.5% from rainfall. This is almost the opposite of the public water supply, which is dominated by surface water supplies (95%) with a smaller contribution from groundwater (5%).

- Ninety-seven per cent of groundwater-sourced potable private water supplies are supported by secondary aquifers. Ordovician and Silurian hydrostratigraphic units and their associated Quaternary aquifers are most important, supporting *c.* 75% of groundwater-sourced potable private water supplies.
- Spatial mapping to Lower Super Output Area (LSOA) shows that private water supplies occur across Wales but are concentrated in more rural areas; in some areas up to 43% of properties can depend upon private water supplies.
- It is estimated that 24.6 Ml day^{-1} of groundwater is abstracted from aquifers for potable private water supply: 23.7 Ml day^{-1} from unlicensed supplies and 0.9 Ml day^{-1} from licensed supplies.
- This study presents the first Wales-wide map of insufficiency of private water supplies following the 2018 drought. In total, 131 reported failures were collated and it is possible that there is significant under-reporting of insufficiency events for private water supplies in Wales. Many of the reported cases were in areas that are underlain by secondary aquifers, which may be vulnerable to prolonged dry weather events.
- To address the challenges of future drought and to improve resilience, monitoring, analysis and modelling of the response of groundwater systems and the use of private water supplies is required.
- There are considerable environmental and societal data gaps relating to small-scale domestic private water supplies in particular; these need to be better understood if the vulnerability of communities reliant on these sources is to be proactively protected under changing climate scenarios.

Acknowledgements The authors would like to thank the Water Health Partnership for Wales, whose members represent each of the 22 local authorities in Wales and include representatives from Dŵr Cymru Welsh Water, Hafren Dyfrdwy, Welsh Government, Water Regulatory Advisory Scheme, Drinking

Water Inspectorate and Natural Resources Wales. Assistance has also been provided by staff at the Drinking Water Inspectorate, J. Sisson from Natural Resources Wales, and D. Schofield and M. Lewis from the British Geological Survey. We extend our thanks to J. Smith and S. Buss for reviewing this paper. G.F. and E.L.A. publish with the permission of the Director, British Geological Survey, UKRI.

Author contributions **GF**: formal analysis (equal), funding acquisition (equal), investigation (equal), methodology (equal), project administration (equal), visualization (equal), writing – original draft (lead), writing – review & editing (equal); **ELA**: formal analysis (equal), funding acquisition (equal), investigation (equal), project administration (equal), writing – original draft (supporting), writing – review & editing (equal); **KJ**: writing – original draft (supporting), writing – review & editing (supporting); **AK**: writing – original draft (supporting), writing – review & editing (supporting); **DAJ**: writing – original draft (supporting), writing – review & editing (supporting); **CJ**: writing – original draft (supporting), writing – review & editing (supporting)

Funding This work was funded by the Natural Environment Research Council, Private water supplies in Wales: information to support public health priorities, NERC Knowledge Exchange NE/NO1751X/1.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability The data that support the findings of this study are available from the Drinking Water Inspectorate but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available.

Scientific editing by Jonathan Smith; Jude Cobbing

References

Allen, D.J., Brewerton, L.J. *et al.* 1997. *The Physical Properties of Major Aquifers in England and Wales*. British Geological Survey, Technical Report, **WD/97/34**. Environment Agency R&D Publication, **8**.

Ander, E.L., Watts, M.J. *et al.* 2016. Variability in the chemistry of private drinking water supplies and the impact of domestic treatment systems on water quality. *Environmental Geochemistry and Health*, **38**, 1313–1332, https://doi.org/10.1007/s10653-016-9798-0

Ander, E.L., Farr, G., James, K. and Kibble, A. 2020. *Private Water Supplies in Wales; Information to Support Public Health Priorities*. British Geological Survey, Commissioned Report **CR/18/135**.

ARUP 2021. *Reducing uncertainty in Private Water Supply demands in Wales*. REP/01. Job Number 278274-00. 23rd April 2021, produced for Welsh Government.

BBC News Online. 2018. UK heatwave dries up water supplies in Llandeilo, residences say, https://www.bbc.co.uk/news/uk-wales-south-west-wales-44935644 [last accessed 19 March 2021].

Bloomfield, J.P. and Marchant, B.P. 2013. Analysis of groundwater drought building on the standardised precipitation index approach. *Hydrology and Earth System Sciences*, **17**, 4769–4787, https://doi.org/10.5194/hess-17-4769-2013

Bryan, K., Ward, S., Roberts, L., White, M.P., Landeg, O., Taylor, T. and McEwen, L. 2020. The health and well-being effects of drought: assessing multi-stakeholder perspectives through narratives from the UK. *Climatic Change*, **163**, 2073–2095, https://doi.org/10.1007/s10584-020-02916-x

Burke, E.J., Perry, R.H.J. and Brown, S.J. 2010. As extreme value analysis of UK drought and projections of change in the future. *Journal of Hydrology*, **388**, 131–143, https://doi.org/10.1016/j.jhydrol.2010.04.035

CCRA. 2017. *UK Climate Change Risk Assessment 2017 Evidence Report. Summary for Wales*, https://www.theccc.org.uk/wp-content/uploads/2016/07/UK-CCRA-2017-Wales-National-Summary.pdf

Cook, C., Gavin, H., Berry, P., Guillod, B., Lange, B., Rey Vicario, D. and Whitehead, P. 2017. *Drought Planning in England: A Primer*. Environmental Change Institute, University of Oxford, Oxford, http://www.mariusdroughtproject.org/wp-content/uploads/2017/09/MaRIUS_Drought_Primer_Online.pdf

Coxon, G., Addor, N. *et al.* 2020. CAMELS-GB: hydrometeorological time series and landscape attributes for 671 catchments in Great Britain. *Earth System Science Data*, **12**, 2459–2483, https://doi.org/10.5194/essd-12-2459-2020

Crabbe, H., Fletcher, T. *et al.* 2017. Hazard ranking method for populations exposed to arsenic in private water supplies: relation to bedrock geology. *International Journal of Environmental Research and Public Health*, **14**, 1490, https://doi.org/10.3390/ijerph14121490

DWI. 2017. *Drinking Water 2016. Private Water Supplies in Wales, July 2017*. Drinking Water Inspectorate, London, https://cdn.dwi.gov.uk/wp-content/uploads/2020/12/07081837/pws-wales-2016-1.pdf

DWI. 2019. *Drinking Water 2018. Summary of the Chief Inspectors Report for Drinking Water in Wales. Private water supplies in Wales, July 2019*. Drinking Water Inspectorate, London, http://www.dwi.gov.uk/about/annual-report/2018/PWS-2018-Wales.pdf

DWQR. 2019. *Drinking Water Quality in Scotland 2018. Private water supplies*. Drinking Water Quality Regulator for Scotland, Edinburgh, https://dwqr.scot/media/43310/dwqr-annual-report-2018-private-supply-final-report-approved-by-sp-for-publication-17-september-20192.pdf

Dwr Cymru Welsh Water. 2019. *Water Resources Management Plan 2019*. Dwr Cymru Welsh Water, Cardiff, https://www.dwrcymru.com/en/our-services/water/water-resources/final-water-resources-management-plan-2019

Environment Agency. 2006. *The Impact of Climate Change on Severe Droughts. Major Droughts in England and Wales from 1800 and Evidence of Impact*. Environment Agency Science Report, **SC040068/SR1**.

Environment Agency. 2009. *Water for people and the environment*. Water Resources Strategy for England and Wales. Environment Agency, Bristol, https://webarchive.nationalarchives.gov.uk/20140328161417; http://cdn.environment-agency.gov.uk/geho0309bpkx-e-e.pdf

Hafren Dyfrdwy. 2019. *Water Resources Management Plan, September 2019*. Hafren Dyfrdwy, https://www.hdcymru.co.uk/content/dam/hdcymru/about-us/wrmp/2019-final/WRMP19-final-eng.pdf

Hiscock, K. and Paci, A. 2000. Groundwater resources in the Quaternary deposits and Lower Palaeozoic bedrock of the Rheidol catchment, west Wales. *Geological Society, London, Special Publications*, **182**, 141–155, https://doi.org/10/1144/GSL.SP.2000.182.01.14

Jasechko, S. and Perrone, D. 2021. Global groundwater wells at risk of running dry. *Science*, **372**, 418–421, https://doi.org/10.1126/science.abc2755

Johnson, T.D. and Belitz, K. 2017. Domestic well locations and populations served in the contiguous U.S.: 1990. *Science of the Total Environment*, **607–608**, 658–668, https://doi.org/10.1016/j.scitotenv.2017.07.018

Jones, D.A. and Farr, G. 2015. Natural Resources Wales' monitoring networks for groundwater level and quality: the story so far. *In*: Bevins, R.E., Nichol, D. and Solera, S.A. (eds) *Urban Geology in Wales. 4*. National Museums of Wales Geological Series, **27**. National Museum of Wales, Cardiff, 217–225.

Jones, H.K., Morris, B.L. *et al.* 2000. *The Physical Properties of Minor Aquifers in England and Wales*. BGS Report, **WD/00/4**. Environment Agency R&D Publication, **68**.

Kendon, M., Marsh, T. and Parry, S. 2013. The 2010–2012 drought in England and Wales. *Weather*, **68**, 88–95, https://doi.org/10.1002/wea.2101

Loveless, S., O'Dochartaigh, B. *et al.* 2019. *Hydro-JULES Task 4.2 Groundwater Conceptual Model Development*. British Geological Survey Internal Report, **OR/19/023**.

Mansour, M.M., Wang, L., Whiteman, M. and Hughes, A.G. 2018. Estimation of spatially distributed groundwater potential recharge for the United Kingdom. *Quarterly Journal of Engineering Geology and Hydrogeology*, **51**, 247–263, https://doi.org/10.1144/qjegh2017-051

Marsh, T., Cole, G. and Wilby, R. 2007. Major droughts in England and Wales, 1800–2006. *Weather*, **62**, 87–93, https://doi.org/10.1002/wea.67

McCarthy, M., Christidis, N. *et al.* 2019. Drivers of the UK summer heatwave of 2018. *Weather*, **74**, 390–396, https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/wea.3628

McDowell, C.P., Andrade, L., O'Neill, E., O'Malley, K., O'Dwyer, J. and Hynds, P.D. 2020. Gender-related differences in flood risk perception and behaviours among private groundwater users in the Republic of Ireland. *International Journal of Environmental Research and Public Health*, **17**, 2072, https://doi.org/10.3390/ijerph17062072

Met Office. 2018. *Case studies of past severe weather events, summer 2018*. Met Office, Exeter, https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2018/summer-2018—met-office.pdf [last accessed 11 December 2019].

Met Office. 2021. *UK Regional Climates. Wales Climate*. Met Office, Exeter, https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/wales_-climate—met-office.pdf [last accessed 7 May 2021].

Mooney, S., O'Dwyer, J., Lavallee, S. and Hynds, P.D. 2021. Private groundwater contamination and extreme weather events: the role of demographics, experience and cognitive factors on risk perceptions of Irish private well users. *Science of the Total Environment*, **784**, 147118, https://doi.org/10.1016/j.scitotenv.2021.147118

Moreau, M., Shand, P., Wilton, N., Brown, S. and Allen, D. 2004. *Baseline Report Series 12: The Devonian Sandstone Aquifer of South Wales and Herefordshire*. British Geological Survey Commissioned Report, **CR/04/185N**.

Murphy, J.M., Sexton, D.M.H. *et al.* 2009. *UK Climate Projections Science Report: Climate Change Projections*. Met Office Hadley Centre, Exeter.

Murti, M., Yard, E., Kramer, R., Haselow, D., Mettler, M., McElvany, R. and Martin, C. 2016. Impact of the 2012 extreme drought conditions on private well owners in the United States, a qualitative analysis. *BMC Public Health*, **16**, 430, https://doi.org/10.1186/s12889-016-3039-4

Neal, C., Robson, A.J. *et al.* 1997. The occurrence of groundwater in the Lower Palaeozoic rocks of upland central Wales. *Hydrology and Earth Systems*, **1**, 3–18, https://doi.org/10.5194/hess-1-3-1997

ONS. 2011. Lower Layer Super Output Areas, December 2011. Office for National Statistics, London, https://geoportal.statistics.gov.uk/datasets/

b7c49538f0464f748dd7137247bbc41c_0?geometry=-16.760%2C50.531%2C12.507%2C55.170 [last accessed 7 May 2021].
ONS. 2017. Population Estimates Wales. Office for National Statistics, London, https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates [last accessed 11 March 2019].
Rickert, R., Samwel, M., Shinee, E., Kožíšek, F. and Schmoll, O. 2016. *Status of Small-Scale Water Supplies in the WHO European Region. Results of a Survey Conducted under the Protocol on Water and Health*. WHO Regional Office for Europe, Copenhagen.
Rivington, M., Akoumianaki, I. and Coull, M. 2020. *Private Water Supplies and Climate Change: the likely impacts of climate change (amount, frequency and distribution of precipitation), and the resilience of private water supplies*. Scotland's Centre of Expertise for Waters (CREW), **CRW2018_05**, https://www.crew.ac.uk/sites/www.crew.ac.uk/files/publication/CRW2018_05_report_FINAL.pdf [last accessed 10 October 2021].
Robins, N.S. 1999. Groundwater occurrence in the Lower Palaeozoic and Precambrian rocks of the UK: implications for source protection. *Water and Environment Journal*, **13**, 447–453, https://doi.org/10.1111/j.1747-6593.1999.tb01084.x
Robins, N.S. and Davies, J. 2016. *Hydrogeology of Wales*. British Geological Survey, Keyworth, Nottingham.
Robins, N.S. and McKenzie, A.A. 2005. Groundwater occurrence and the distribution of wells and springs in Precambrian and Palaeozoic rocks, NW Anglesey. *Quarterly Journal of Engineering Geology and Hydrogeology*, **38**, 83–88, https://doi.org/10.1144/1470-9236/04-064
Robins, N.S., Shand, P. and Mettin, P.D. 2000. Shallow groundwater in drift and Lower Palaeozoic bedrock: the Afon Teifi valley in west Wales. *Geological Society, London, Special Publications*, **182**, 123–131, https://doi.org/10.1144/GSL.SP.2000.182.01.12
Robins, N.S., Davies, J., Cheney, C. and Tribe, E.L. 2007. Groundwater in a water rich environment: Wales, a land of plenty. *Water and Environment Journal*, **19**, 62–67, https://doi.org/10.1111/j.1747-6593.2005.tb00550.x
Shand, P., Abesser, C. *et al.* 2005. *Baseline Report Series. 17, the Ordovician and Silurian Meta-Sedimentary Aquifers of Central and South-West Wales*. Environment Agency, **CR/05/034N**.
The Private Water Supply (Wales) Regulations 2010. https://www.legislation.gov.uk/wsi/2010/66/regulation/8/made
The Private Water Supply (Wales) Regulations 2017. https://www.legislation.gov.uk/wsi/2017/1041/regulation/17/made
Turner, S., Barker, L.J., Hannford, J., Muchan, K., Parry, S. and Sefton, C. 2021. The 2018/2019 drought in the UK: a hydrological appraisal. *Weather*, **76**, 248–253, https://doi.org/10.1002/wea.4003
Waddington, K. 2017. 'I should have thought that Wales was a wet part of the world': Drought, Rural Communities and Public Health, 1870–1914. *Social History of Medicine*, **30**, 590–611, https://doi.org/10.1093/shm/hkw118
Water UK. 2020. Be 'water aware' – tips for people at home. Water UK, London, https://www.water.org.uk/news-item/be-water-aware-tips-for-people-at-home/
Welsh Government. 2015. *Water Strategy for Wales. Supporting the Sustainable Management of Our Natural Resources*. Welsh Government, Cardiff, https://gov.wales/sites/default/files/publications/2019-06/water-strategy.pdf
Welsh Government. 2019. *Agriculture in Wales, 2019*. Welsh Government, Cardiff, https://gov.wales/sites/default/files/publications/2019-06/agriculture-in-wales-evidence.pdf