Protection of Small Private Supplies in Ireland

Key contaminants of concern, how they can be prevented/managed, and how to successfully communicate with and support supply owners

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Executive Summary

Recent reports by the Environmental Protection Agency (EPA) indicate the deterioration of surface and groundwater quality in Ireland from 2013 to 2019 (EPA, 2020a). In that context, supporting small-scale water supply owners is crucial to safeguarding public health, particularly as several contaminants are associated with potentially severe health issues. In Ireland, Small Private Supplies (SPSs) are those which produce a volume of water greater than 10 m^3/day or serve 50 or more people in commercial or public activities (e.g. hotels, B&Bs, pubs, creches, schools, campsites, etc.). Despite being under the supervision of corresponding Local Authorities (LAs), these mostly groundwater-derived supplies consistently display the poorest water quality of all regulated supply types (EPA, 2020b, EPA, 2021). This may be attributable to insufficient engagement with appropriate source protection and maintenance practices (including treatment, where required). Accordingly, the current report aims to (i) identify recurring and persistent (*key*) contaminants within Irish groundwaters and SPSs using EPA and LAs' monitoring data, (ii) review the scientific literature and current policy to determine the main evidence-based well stewardship practices available for prevention (and/or management) of *key contaminants*, and (iii) propose communication strategies which may be used to motivate and promote desirable well stewardship practices based on a thorough review of relevant literature and expert opinion.

The three *key contaminants* (i.e. most frequently found exceeding permissible concentrations; EC, 1998) within regulated SPSs and monitored groundwaters from 2014-2019 were:

- *Escherichia coli* (and other faecal coliforms): These are bacteria commonly used to indicate faecal contamination (likely from nearby agriculture and/or domestic wastewater treatment systems) and potential presence of pathogenic microorganisms.
- Arsenic: A carcinogenic metalloid that occurs naturally in groundwater under specific geological conditions and linked with an array of health issues stemming from acute and/or long-term exposure (from abdominal pain and diarrhoea to increased risk of cancer and cardiovascular diseases) .
- Nitrate: A by-product of agricultural activities, mainly fertiliser application, which may in rare cases cause serious illnesses, such as methemoglobinemia (or "blue baby syndrome") in babies, and colorectal cancer and thyroid disease in adults.

To prevent the ingress of the above, and indeed many other, contaminants to groundwater supplies used for human consumption (the most common type amongst SPSs) the following are recommended:

1) **Supply location/settings**: supplies should be at minimum setback distances from potential contamination sources (e.g. farmyards, domestic wastewater treatment systems, industrial activities, etc.) and located in a mounded area, with ground sloping away from it. The area surrounding (within 10 m of) a supply should also be grassed, fenced (to avoid animal access), and kept free of debris.
2) **Protective features**: Supplies should comprise an appropriately sealed vermin-proof cap, and crack-free casing made of steel or PVC, which is elevated by at least 30 cm above the chamber floor. Supply chambers should be made of concrete and constructed above ground with a fitted cover; chamber walls and floor must be kept dry, clean, and crack-free.
3) **Drilling process**: Deeper wells (>30 m) are recommended to prevent contaminant ingress via interflow and (generalised or preferential) recharge. However, where there is risk of groundwater quality deterioration with depth due to geogenic contaminants (e.g. arsenic), employing the assistance of a qualified hydrogeologist during the drilling process is strongly advised. To encourage these measures and the recommended supply location and protective features described in items 1 and 2, step-by-step guidelines on well construction should be made widely available to current and future private supply owners.
4) **Maintenance**: It is recommended that supply waters are tested annually, preferably following periods of intense rainfall and/or extreme weather events, and at least twice per year for indicator contaminants such as E. coli. This monitoring frequency is already mandatory for SPSs and must be carried out by supply owners themselves or LAs, however enforcement by LAs is insufficient as evidenced in recent EPA reports (EPA, 2015; 2017b; 2020b; 2021). Test results will inform whether further source protection and/or treatments are needed, as such test interpretation guidelines should be provided and widely available. Moreover, where SPS contamination issues are identified, audits should be carried out to identify contamination risks and provide tailored recommendations (including with regards to treatment) as recommended by the EPA (EPA, 2021). It is also advised that the supply, its surrounding area, and drinking water treatment systems (where present) are inspected/serviced annually to prevent instances of contamination.
5) **External management practices**: The risk of contamination to wells can also be lowered through appropriate management of potential nearby sources of contamination. For this, guidance on appropriate agricultural practices (see regulations in Good Agricultural Practices for the Protection of Waters document; European Union, 2017a) and domestic wastewater treatment system maintenance (see Code of Practice for Wastewater

Treatment Systems for Single Houses; EPA, 2010) must be stringently applied and enforced either directly by the EPA and LAs, or through relevant custodians at the community level such as advisors in the Teagasc Agricultural Sustainability Support and Advisory Programme (ASSAP). These guidelines should also be kept up-to-date.

In cases where source protection measures alone are not sufficient to prevent contamination, alternative management practices (further described in Section 5 of this report, including treatment) are available and should be employed by SPS owners, with appropriate guidance and enforcement by LAs (EPA, 2021).

The promotion of well stewardship is a complex matter as there are many barriers to the uptake of the desired practices described above. To manage these, more resources than those presently available to supervisory authorities (i.e. LAs) are required, as evidenced in EPA private supply reports (EPA, 2015; 2017b; 2020b; 2021). Current lack of longstanding departmental structures and monetary funding, and limitations in organisation knowledge specific to SPS issues, for example, represent key hinderances to long-term well-stewardship promotion and enforcement (Mooney et al., 2020). As such, a key recommendation of this research is that a specific governance organisation is formed to provide overarching guidance and support for SPSs nationally, and to work alongside LAs at the regional and community levels. For this, a similar governance structure to that employed by the National Federation Group Water Scheme (NFGWS), which works closely with Group Water Schemes across the country, may be utilised. Principal recommended responsibilities of this new organisation, based on issues identified in the current study, should include:

1) **Register all Small Private Supplies in the country.**
2) **Produce hotspot maps for naturally occurring groundwater contaminants (e.g. arsenic) and enforce/promote assistance of a qualified hydrogeologist during the drilling of new supplies in high-risk areas.**
3) **Enforce source protection, and relevant agricultural and domestic wastewater treatment regulations**, including minimum setback distances to drinking water supplies, with changes (where applicable) to the Good Agricultural Practices for the Protection of Waters and Code of Practice for Wastewater Treatment Systems for Single Houses.
4) **Update/create regulatory and communication documents in line with evidence-based recommendations, which**:
    - Clearly outline the risks of contamination to groundwater supplies and consumers,

- Provide step-by-step evidence-based guidance regarding supply protection/ management (including well construction and maintenance, water test interpretation, treatment options, etc.), and
- List registered service providers.

5) **Organise periodic well stewardship dissemination campaigns at the national, regional and local levels** using traditional and social media; mailing and/or emailing; workshops; stands at relevant events (e.g. ploughing championship); school events; and/or citizen science initiatives (this may be particularly effective with regards to the water testing behaviour). Campaigns should also be periodically (annually/biannually) evaluated, not only to measure progress but also to improve subsequent messages, and dissemination/engagement mechanisms.
6) **Ensure that all Small Private Supplies with compliance issues are audited/inspected.** During these visits, contamination risks should be identified and tailored recommendations regarding source protection and treatment, where needed, should be provided.
7) **Support, train, and coordinate relationships between relevant stakeholders at national, regional and local levels**, ranging from public and private organizations to service providers.
8) **Provide official training and registration of service providers** (e.g. well drillers, water testing facilities, treatment installation companies etc), with registration upon successful completion of training. Lists of registered providers can then be made available to Small Private Supply owners.
9) **Provide continuous support to Small Private Supply owners** via helplines or other assistance systems at the local level (e.g. local advisors).

1. Background

In the Republic of Ireland, the different types of water supply available are clearly defined (**Table 1**). Of these, (private) household wells are the only unregulated supply type, with sole responsibility of water provision and potability lying with well owners. The remaining supply types are regulated by the Environmental Protection Agency (EPA) and/or Local Authorities (LAs) (EPA, 2015). Monitoring data from these two supervisory authorities show that Private Group Water Schemes (PrGWSs) and Small Private Supplies (SPSs) exhibit the lowest drinking water quality, with non-compliance found in 5% and 8% of registered supplies, respectively, in 2018 (EPA, 2020b). This is attributed to the fact that both PrGWSs and SPS are entirely managed (including abstraction, treatment, and distribution), by their owners (i.e. local communities and commercial/public entities, respectively) (EPA, 2015).

Table 1: Water suppliers available in Ireland (adapted from EPA, 2015)

Water Supply type	Number of registered supplies in 2013	Responsible for abstraction and treatment	Responsible for abstraction	Supervisory Authorities
Public Water Supplies	978	Irish Water	Irish Water	Environmental Protection Agency
Public Group Water Schemes	614	Irish Water	Local group	Local Authorities, NFGWS
Private Group Water Schemes	438	Local group	Local group	Local Authorities, NFGWS
Small Private Supplies	1,801	Private/ public entity	Commercial/ public entity	Local Authorities
Household Wells	>170,000	Individual supplier	Individual supplier	Unregulated

In recent years, significant progress has been made in protecting the quality of drinking waters from PrGWSs, with the implementation of a Source Protection Pilot Project by the National Federation of Group Water Schemes (NFGWS, 2019). However, no similar support is available to SPSs, and as such, their water quality remains consistently poorer. Issues arise from inadequate treatment, and lack of knowledge regarding source protection measures. There are over 1,750 registered SPSs in 2019 servicing many private and public buildings, including hotels, B&Bs, pubs, creches, schools, campsites, etc. (EPA, 2021), and it is crucial that the water they supply is of acceptable quality to prevent adverse human health impacts. This is of particular concern where vulnerable sub-populations may be exposed, such as children under 5 and the elderly (Figueiras and Borrego, 2010; Murphy et al., 2017).

Accordingly, this study sought to review current knowledge and provide best-practice recommendations to ensure the water quality of SPSs. For this, information from SPS monitoring, collated by LAs, and the EPA Groundwater Monitoring Programme, as over 90% of registered SPSs are groundwater-derived (EPA, 2017b), were assessed. Data pertaining to the 6-year period from 2014 to 2019, where available, were used to identify *key contaminants* - i.e. those frequently exceeding the maximum permissible concentrations (MPC) determined by the European Union (EU) Drinking Water Directive 98/83/EC (EC, 1998). Once established, policy and academic literature were reviewed and translated into source protection and management recommendations specific to each key contaminant. Finally, relevant literature was used to recommend effective strategies for communicating and motivating SPS owners to protect their water sources and prevent potential health issues.

2. Objectives

This project aimed to

1) Identify the *key contaminants* most frequent in SPSs in the Republic of Ireland,
2) Ascertain how these can be managed through source protection (or other management) practices, and
3) Suggest effective communication strategies to promote drinking water protection.

This was achieved through the completion of the following specific objectives:

- Identify the most prevalent contaminants in Irish SPSs under the auspices of the EU Drinking Water Directive (EC, 1998),
- Identify evidence-based source protection measures and, where source protection is not sufficient, alternative management (including treatment) options, and
- Identify successful communication strategies available in the literature which promote source protection and would be applicable to the Irish context.

As most the over 1,750 SPSs registered in Ireland in 2019 are groundwater wells (EPA, 2021), these were the focus of this study. As such, recommendations are also applicable to domestic (household) wells and any other small-scale groundwater abstraction. Surface water SPSs can also benefit from information present in this report, particularly with regards to available treatment options.

3. Methodology

3.1. Identification of key contaminants

Data collated by the EPA and LAs, which specify results for groundwater and SPS water monitoring from 2014 to 2019 were examined. Both datasets were summarised based on exceedance of permissible concentrations for microbial and chemical contaminants in accordance with the EU Drinking Water Directive (EC, 1998). Contaminants which have most frequently exceeded MPC were deemed *key contaminants* of concern.

3.1.1. National groundwater monitoring programme

In the Republic of Ireland, the EPA Groundwater Monitoring Programme has used drilled wells (i.e. boreholes) dispersed through the country to monitor Irish aquifers for over 20 years, with particular focus on parameters specifically alluded to in the EU Drinking Water Directive. The open-access EPA dataset for the national groundwater monitoring programme (available at http://gis.epa.ie/) provided detailed information for each sample collected including date, location (county, monitoring station, and coordinates), and results for multiple biological and physio-chemical parameters. In this report, monitoring data from 2014 to 2019, inclusive, were used to examine the main water quality issues in recent years. In total, over the study period, 4,809 groundwater samples were collected from 276 monitoring boreholes (also known as monitoring stations) across the country. However, not all samples were tested for all parameters; notably at the time of data extraction for this study the 2019 dataset only comprised test results for faecal coliforms, nitrate (NO_3) and nitrite (NO_2).

In this study, as mentioned previously, only the microbiological and chemical contaminants listed in the EU Drinking Water Directive were examined. Where measured contaminant concentrations were available for <10% of samples collected during any particular year, these were not included for analyses. Accordingly, thirteen parameters (all tested in >85% of annual samples) were included (see **Table 2**)

Table 2: Microbiological and Chemical contaminants assessed using data from the EPA Groundwater Monitoring Programme

Microbiological	Faecal coliforms
Chemical	Antimony, Arsenic, Boron, Cadmium, Chromium, Copper, Fluoride, Lead, Mercury, Nickel, Nitrate, and Nitrite

To simplify data analyses, all contaminant results were coded as binary records (i.e. below/above maximum permissible concentrations (MPCs) according to EU Drinking Water Directive; EC, 1998). An abridged dataset was produced in MS Excel which included the percentage of sampling stations exceeding MPCs for each contaminant at least once in each year under study. No county subdivisions were employed, as sample and monitoring station numbers were not consistent. County Westmeath, for example, only has one monitoring station, while there are 35 in county Cork. Percentage of samples exceeding MPC yearly were also not used in this study as this could introduce biases, with sample numbers varying from year to year, and particular monitoring stations having been sampled more often than others.

3.1.2. Small drinking water supply monitoring

Monitoring data for SPSs are collated yearly by the LAs (available at http://erc.epa.ie/safer/), which outlines the number of supplies and samples exceeding MPC for specific monitoring parameters; in line with the EC Drinking Water Directive regulations. In this study, available datasets for the study period were extracted and summarised for the entire country. County sub-divisions were once again not used due to potential bias due to the varying number of SPSs registered with each LA. Contaminants which had been tested in less than 10% of supplies in most studied years were not included in this study. The final list of contaminants included for analyses is shown in **Table 3**, with only *E. coli* and *nitrate* results being reported consistently in over 40% of sampled SPSs annually.

Table 3: Microbiological and Chemical contaminants assessed from Small Private Supplies monitoring data collated by Local Authorities

Microbiological	*Escherichia coli*
Chemical	Arsenic, Copper, Lead, Nickel, Nitrate

Limitations must be acknowledged regarding this dataset as no information was provided on specific supply location or supply type (i.e. surface or groundwater). Moreover, samples were collected after treatment, where present, and not all SPSs have been consistently included within the annual datasets (with data missing from certain counties for certain years). As such, these data can be used only as an indicator of drinking water quality in SPSs and not as a tool for examining which contaminants are most present at source.

3.2. Identification of source protection measures

To identify appropriate source protection measures associated with recurring (key) contaminants, peer-reviewed literature was sought which examine common factors associated with the presence of each of these *key contaminants*. For this, systematic and scoping review techniques were combined to locate relevant reviews and Irish-specific literature. A total of 6 searches were performed using the

Web of Science database (see **Appendix 1.** Database searches for identification of issues associated with the occurrence of *key contaminants* for full description, and **Figure 1** for a workflow summary) with noted differences in search terms between anthropogenic (i.e. caused by human activities) and geogenic contaminants (i.e. those occurring naturally in soil and groundwater due to local geology); this differentiation was employed as source protection measures are not applicable for geogenic contaminants, and thus, other management strategies are required.

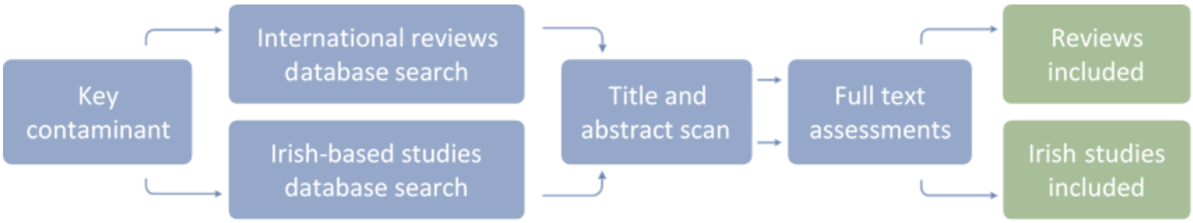

Figure 1: Schematic of the literature review process

From each of the performed searches, included studies were those that explored contaminant ingress mechanisms to groundwater supplies, or management strategies used to prevent and/or mitigate supply contamination. Study inclusion was evaluated during the two screening stages described in **Figure 1**, namely, scan of title and abstracts followed by full-text examination to ensure relevance. Data from included studies were then extracted and interpreted. Translation of literature review findings into source protection measures were also based on source construction and maintenance recommendations currently available to Irish private suppliers through the EPA. Guidelines available from other countries were also examined to identify relevant recommendations.

3.3. Identification of effective communication strategies

The identification of effective strategies for the communication of SPS source protection measures was based on recent peer review literature recommendations, with a similar methodology to the one described in Section 3.2 above, employed. Briefly, relevant (and recent) reviews and Irish-specific studies were sought using merged systematic and scoping review techniques. Studies included were those that examined previous communication initiatives and/or recommended communication practises in the context of private groundwater source protection. Searches were performed using the Web of Science database (see **Appendix 2.** Database searches for identification of effective communication strategies) and study eligibility was determined using during two consecutive stages, namely, scan of title/abstracts and full-text examination (**Figure 1**).

4. Key contaminants

As outlined in Section 3.1, the main objective in analysing EPA and LAs monitoring data was to identify the contaminant exceedances most commonly encountered in Irish groundwaters and registered SPSs, respectively. Analyses identified three contaminants which were consistently present in concentrations exceeding MPCs (EC, 1998) in both datasets during the 6-year period examined; namely, faecal coliforms (including *E. coli*), nitrate, and arsenic. Of these, faecal coliforms exhibited the highest contamination rates, with 69.6% of groundwater monitoring wells across the country having exceeded the current MPC (of 0/100ml; EC, 1998) at least once between 2014 and 2019, and 4.3 to 6.8% of drinking water from SPSs exceeding it annually.

4.1. Key contaminants in Irish groundwaters

As shown (**Table 4**), faecal coliforms consistently exceeded MPCs, ranging from 37.8 to 45.8% annually between 2014 to 2019. Arsenic (As) and nitrate (NO_3) were the second and third most frequently exceeded contaminants, exceeding MPCs at up to 3.0% and 2.6% of monitoring stations in a year, respectively. Nickel was the fourth most prevalent contaminant (exceeding parametric vales at least once in 2.2% of monitoring stations during the study period), however this was attributed to a marked increase in 2016 (and particularly during March and October, data not shown) with exceedance levels having remained low since then. Nitrite (NO_2), fluoride, lead (Pb) and antimony were found in exceedance in just 1.8, 0.7, 0.7 and 0.4% of monitoring stations during the studied period, respectively. No other contaminants studied (see **Table 2**) were found above MPCs in any of the monitoring stations during the same period, namely, boron, chromium, copper, cadmium, and mercury.

Table 4: Summary of EPA Groundwater Monitoring Programme data showing percentages of monitoring stations exceeding permissible contaminant concentrations at least once annually and in the period from 2014 to 2019.

	2014		2015		2016		2017		2018		2019		2014-2019	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%*
Faecal Coliforms	275	**45.8%**	275	**37.8%**	268	**41.8%**	272	**41.9%**	272	**45.6%**	270	**42.2%**	276	**69.6%**
Nitrite (NO_2)	275	0.7%	275	0.7%	269	0.4%	272	0.0%	272	0.7%	271	0.4%	276	**1.8%**
Nitrate (NO_3)	275	**1.1%**	275	0.7%	269	**1.1%**	272	**1.1%**	272	**2.6%**	271	**2.6%**	276	**4.0%**
Fluoride	275	0.7%	275	0.7%	269	0.7%	272	0.7%	272	0.4%	271	0.7%	276	0.7%
Boron	275	0.0%	275	0.0%	269	0.0%	272	0.0%	263	0.0%	0	-	276	0.0%
Chromium	275	0.0%	275	0.0%	269	0.0%	272	0.0%	263	0.0%	0	-	276	0.0%
Nickel	275	0.4%	275	0.7%	269	**1.5%**	272	0.4%	263	0.0%	0	-	276	**2.2%**
Copper	275	0.0%	275	0.0%	269	0.0%	272	0.0%	263	0.0%	0	-	276	0.0%
Arsenic	275	**2.5%**	275	**2.9%**	269	**3.0%**	272	**2.9%**	263	**2.7%**	0	-	276	**4.3%**
Cadmium	275	0.0%	275	0.0%	269	0.0%	272	0.0%	263	0.0%	0	-	276	0.0%
Antimony	275	0.4%	275	0.4%	269	0.4%	272	0.4%	263	0.4%	0	-	276	0.4%
Lead	275	0.0%	275	0.4%	269	0.0%	272	0.4%	263	0.0%	0	-	276	0.7%
Mercury	275	0.0%	275	0.0%	269	0.0%	272	0.0%	242	0.0%	0	-	276	0.0%

n = number of monitoring stations tested for a given contaminant, % = percentage of monitoring stations exceeding parametric values for a contaminant at least once in the year, %* = percentage of monitoring stations exceeding parametric values for a contaminant at least once in the entire study period (i.e. from 2014 to 2019). Values in red font are those that exceed 1%.

As shown (**Figure 2**), mean faecal coliform contaminations above MPCs were widespread across the country during the study period, with highest mean concentrations (i.e. > 200 MPN/100ml) seen in the north-west of the country. As nitrate and arsenic presence were not as prevalent, 95th percentile concentrations among all collected samples in the study period were used, instead of means, to indicate 'worst case scenarios' and highlight potential at-risk areas. **Figure 3a** shows that elevated nitrate contamination occurs mostly in the south and south-east of the country, where agricultural activities are more intense (EPA, 2020a). With regards to arsenic, **Figure 3b** shows areas of highest risk in the south, north-east, and (to a lesser extent) in the north-west of Ireland. These results are in line with findings from other studies of arsenic contamination in the country (McGrory et al., 2017), however more research is needed to analytically categorise areas of arsenic-hotspots.

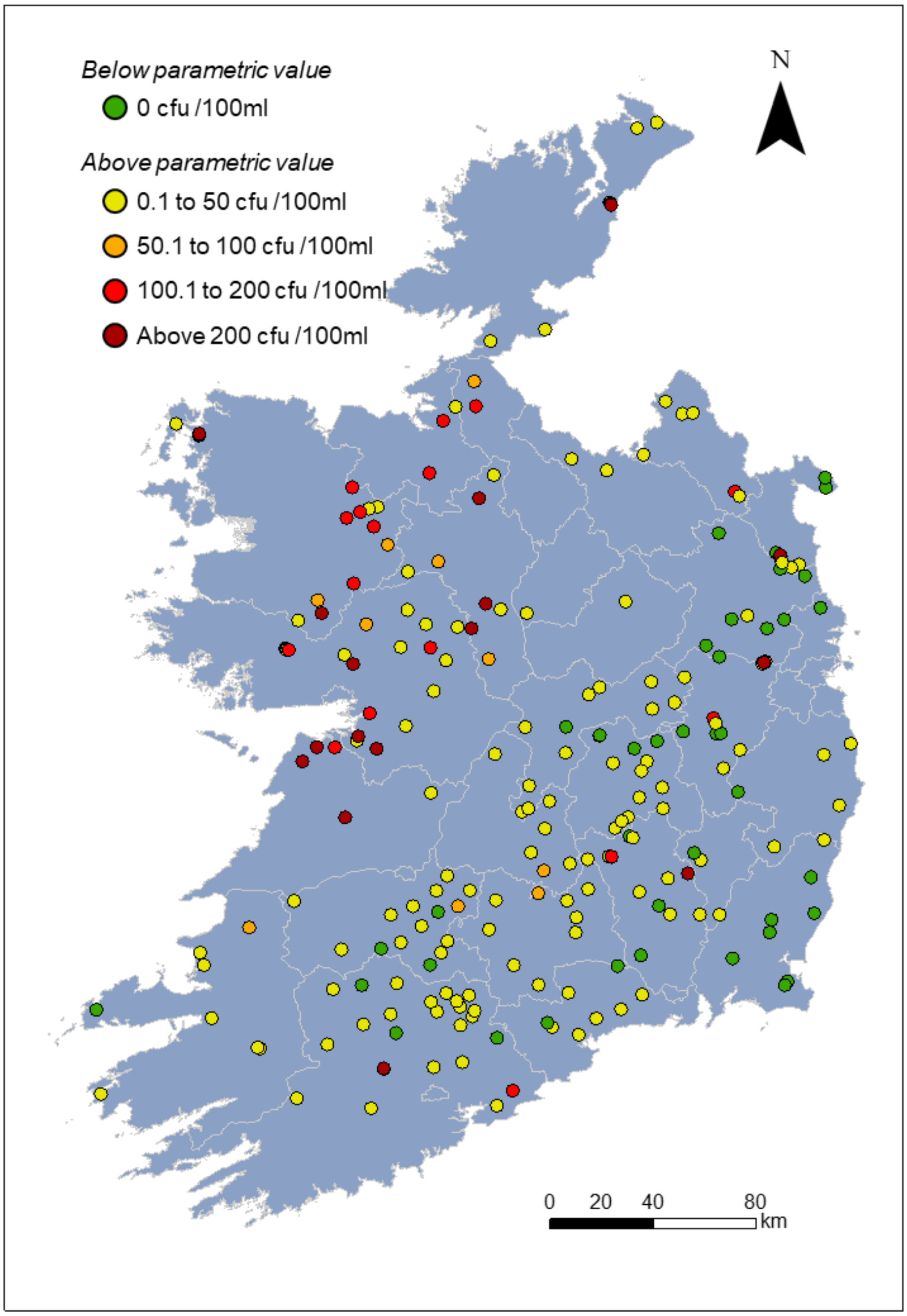

Figure 2 Map showing mean faecal coliform concentrations in groundwater samples from stations monitored by the EPA Groundwater Monitoring Programme in the Republic of Ireland in the period from 2014 to 2019.

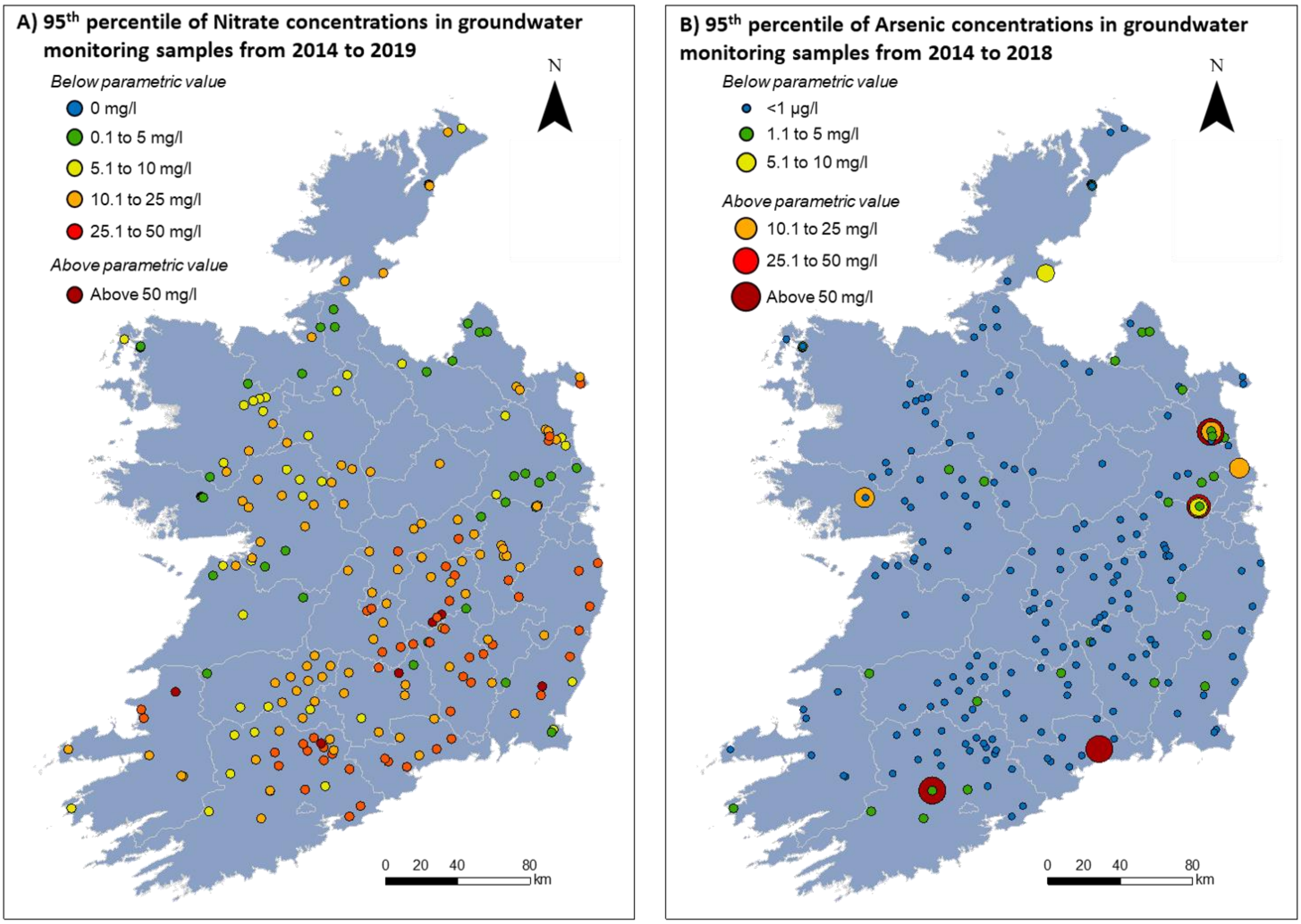

Figure 3: Maps showing (A) 95th percentile of nitrate (NO_3) concentrations in groundwater samples taken from stations monitored by the EPA Groundwater Monitoring Programme from 2014 to 2019; and (B) 95th percentile of arsenic concentrations in groundwater samples taken from stations monitored by the EPA Groundwater Monitoring Programme from 2014 to 2018 in the Republic of Ireland

The most frequently exceeded contaminants found in Irish groundwaters, described in this report, highlight the principal threats to SPSs across the country. These may be used to inform the development of vital source-protection and contaminant management measures. In arsenic hotspot areas, for example, regular arsenic testing and appropriate management practices should be encouraged.

4.2. Key contaminants in small private supplies

Country-wide data describing water quality assessment for regulated SPSs during the studied period are summarised in **Table 5**. As expected, *E. coli* tests were the most common, followed by nitrate. During the entire study period, copper and lead (Pb) were tested by over 10% of regulated SPSs yearly, and in recent years (i.e. since 2017 and 2018, respectively) the same is true for arsenic and nickel. This may be attributable to EU Drinking Water Regulations amendments made in 2017 (EU, 2014; 2017b) which resulted in changes to the list of required parameters and sample frequencies in SPSs.

Information regarding monitoring frequency for each parameter is relevant as numbers of non-compliant SPSs are likely higher than reported and annual compliance rates may not be representative (i.e. they may be lower or higher than in reality) due to lack of testing.

Table 5: Summary of drinking water monitoring data collated by Local Authorities showing percentages of registered Small Private Supplies exceeding permissible contaminant concentrations annually from 2014 to 2019.

	2014		2015		2016		2017		2018		2019*	
	n	%	n	%	n	%	n	%	n	%	n	%
Escherichia coli	1111	**6.8%**	896	**5.2%**	1097	**5.2%**	1186	**4.3%**	1356	**4.6%**	1512	**5.6%**
Nitrate (NO_3)	767	**1.0%**	651	**1.2%**	459	**1.3%**	537	**2.4%**	707	**1.8%**	732	**2.9%**
Nickel	23	0.0%	40	0.0%	76	**1.3%**	107	0.9%	170	**1.2%**	334	0.0%
Copper	247	0.8%	165	0.6%	126	**2.4%**	137	0.7%	238	**1.3%**	377	0.3%
Arsenic	20	0.0%	40	0.0%	86	**3.5%**	119	0.8%	166	**1.2%**	336	0.6%
Lead	296	0.0%	293	**1.0%**	211	**1.4%**	203	0.0%	288	**1.7%**	536	0.9%

n = number of small private suppliers (SPSs) tested for a given contaminant, % = percentage of SPSs exceeding parametric values for a contaminant. Values in red font are those that exceed 1%.

During the study period, *E coli* exceedance was the most common, ranging from 4.3 to 6.8% of SPSs over the study period, this was followed by the 1.0 to 2.4% of SPS which exceeded nitrate MPCs each year. As shown in **Table 5**, the years 2016 and 2018 had a marked increase in nickel, copper, arsenic and lead exceedance. It is worth noting that these were years affected by extreme weather events in Ireland, namely, extensive winter flooding in 2015/2016 and prolonged summer droughts in 2018. However, due to the nature of the datasets, it is not possible to ascertain whether these were indeed the circumstances which drove the higher exceedance rates reported. Moreover, as samples were collected after treatment, where present, results cannot be used to identify recurring contaminants at source, it also cannot be stated whether different SPSs have been found non-compliant at different years or the same SPSs have consistently exceeded contaminant thresholds yearly.

5. Measures to protect supplies from contamination

In Ireland, general guidance, and recommendations for source protection of private groundwater supplies (i.e. wells) are available, which address both well construction and maintenance practices. Briefly, with regards to well construction (which according to the EPA is the most common cause of problems associated with private wells) (EPA, 2014a) it is recommended that the Institute of Geologists of Ireland (IGI) guidelines are followed (IGI, 2007; EPA, 2013). These guidelines describe testing, sampling, and abandonment protocols, and appropriate supply location and construction, which apply to any groundwater well used for human consumption, including private household wells, SPSs and GWSs. IGI guidelines are, in theory, aimed at private well owners, well drillers, GWS organisers, consultants, public authorities, and other interested parties, however the length and descriptive narrative used may in parts be too dense for non-experts. A more simplistic description of desired source construction and maintenance practices is also available to private supply owners in leaflet format (EPA, 2017a). However, in both cases the information is not actively publicised, and as such will only reach those who seek it.

With regards to SPSs, it is mandatory that specific water quality parameters are monitored for annually (EU, 2017b; EPA, 2017b), however, as demonstrated by the varying number of SPS monitoring results reported by LAs annually this is not consistently reinforced, particularly as many SPSs remain un-registered. According to current regulations, LAs may also, at their discretion, undertake audits where both protection of the source and treatment are inspected. During these investigations, auditors can make improvement recommendations (EPA, 2017b), however this is infrequently done due to LA resource limitations. Where supplies are unregulated (i.e. household wells) each supply owner is responsible for their well water quality, nonetheless LAs are still responsible for providing advice and guidance where requested (EPA, 2014a).

Despite these available resources, however, as shown in the previous section, issues still exist, with some contaminants exceeding MPCs among SPSs. This may indicate (i) that source protection measures recommended are not sufficient, or (ii) that these are not being sufficiently communicated to and implemented by SPS owners. To identify where the issue lies, in this section, specific literature pertaining to the *key contaminants* (i.e. faecal coliforms, nitrate and arsenic) is summarised and interpreted to provide information on how they may enter groundwater supplies, and how their presence in SPSs can be prevented (or managed). Here, the authors also highlight the health issues that may arise from exposure to each of these contaminants and the importance of specific protective features and management (including treatment) practices to ensure that SPS waters are of acceptable drinking quality.

5.1. *Escherichia coli* and other microorganisms of faecal origin

Escherichia coli (or *E. coli*) is a faecal indicator organism, with their presence used to indicate recent ingress of faecal material and that other faecal contaminants may also be present (including pathogenic microorganisms). Moreover, *E. coli* can in rarer cases also cause illness in humans, as is the case for the Verotoxigenic *E. coli* (VTEC) strain. Exposure to VTEC may lead to a potentially serious infectious disease, for which Ireland currently reports the highest incidence rates in Europe, and which has been significantly associated with private well usage in this country (ÓhAiseadha *et al.*, 2017). Evidence also exists which link consumption of water from private supplies in Ireland and abroad with outbreaks from other pathogens of faecal origin (e.g. campylobacteriosis, cryptosporidiosis, giardiasis) (Denis et al., 2009; Murphy et al., 2016). These pathogens can cause mild to severe cases of gastrointestinal illness, the latter being particularly worrying where vulnerable sub-populations are present such as children under 5 and persons over 65 years of age. Thus, findings from Section 4 showing that *E. coli* frequently exceed permissible values (i.e. > 0/100ml) among SPSs represents a serious public health concern.

The primary sources of faecal contaminants (including pathogenic microorganisms) found in groundwater supplies are agricultural activities and domestic wastewater treatment systems (DWWTSs) (Hynds et al., 2014a; Murphy et al., 2017; Chique et al., 2020b; Chique et al., 2020a). As such, it is recommended that drinking supplies are located as far from these as practical. EPA guidelines for minimum setback distances under varying gradient condition (i.e. upgradient, downgradient and level) are shown in **Table 6**. In the case of septic tanks, however, a study by Hynds et al., (2012) found that "zones of potential impact" can be increased during periods of high-intensity rainfall and suggested higher setback distances to account for those higher-risk periods (see **Table 6**), particularly as they may become more common as a consequence of climate change (Pall et al., 2011; Arnell and Gosling, 2016). Similar "zone of impact" increases can also be assumed for point and nonpoint agricultural sources, despite the lack of specific literature. Of the conventional agricultural practices, livestock farming and slurry spreading are the most cited sources of pathogenic microorganisms in groundwater wells (Hynds et al., 2014b; O'Dwyer et al., 2018; Reynolds et al., 2020), however other point-sources, such as storage sheds, dungsteads, silage pits and animal housing have also been shown to present risks of contamination if located too close to a supply (Hynds et al., 2012; Hynds et al., 2014b). Appropriate distances (> 100 m) should also be kept from surface waters such as streams, rivers, lakes, etc., as these may carry faecal contaminants and can lead to nearby groundwater contamination (Hynds et al., 2014b), particularly in areas where groundwater is under direct influence of surface waters, such as (epi)karst settings (Stokdyk et al., 2020).

Table 6: Minimum recommended setback distances from drinking groundwater supplies to domestic wastewater treatment systems and farmyards

	Minimum setback distances (IGI, 2007)		Minimum setback distances (Hynds et al., 2012)	
	Domestic Wastewater Treatment System	Farmyard	Domestic Wastewater Treatment System	Farmyard
Down-gradient well	60 m	150 m	110 m*	-
Up-gradient well	15 m	50 m	40 m*	-

* increased setback distances based on scenario analyses of atypically high precipitation periods (i.e. 100mm in 120h)

Safe setback distances to potential sources of faecal contamination are extremely important because they allow for natural contaminant attenuation as it flows (or is carried) towards a supply. In other words, contaminants are diluted, filtered and/or dispersed as travel distances through or above the soil increase, and higher residence times in soil and water negatively affect pathogen survival (i.e. die-off rates increase). Thus, agricultural activities such as fertiliser/manure storage and spreading should be restricted in the vicinity of groundwater supplies, particularly those used for human consumption. In Ireland, distances between groundwater abstraction points for human consumption (such as GWSs and SPSs) and manure storage and application must exceed 250 and 100 m, respectively (EU, 2017a). However, it is worth noting that in the case of private household wells these minimum setback distances decrease to 50 and 25 m (EU, 2017a), making these considerably more susceptible to agricultural contamination. With regards to DWWTSs, ubiquitous in rural households in Ireland (CSO, 2017), failure to engage with appropriate maintenance practices (e.g. regular septic tank desludging) also increases exposure of nearby supplies to faecal contamination (Naughton and Hynds, 2014). In 2013, the EPA initiated a *National Inspection Plan* to register and inspect all DWWTSs in use however, despite efforts, maintenance rates across the country have remained mostly unchanged, and even decreased in some places by as much as 5% (Hynds et al. 2018). As such, increased engagement and communication are needed to promote appropriate DWWTS maintenance to prevent contamination of nearby drinking supplies.

There are a number of potential pathways (or ingress mechanisms) which may allow contaminants from nearby agriculture or DWWTSs to enter groundwater supplies, with the four most significant described below:

1) **Aquifer contamination**: this describes instances where the underlaying aquifer (i.e. the geological formations that store groundwater underground) becomes contaminated. Where this occurs, all wells extracting water from the aquifer may be compromised. This

ingress mechanism is the most serious, as source protection measures are not available to prevent contamination.

2) **Generalised (non-preferential) recharge:** this refers to the gradual gravitational percolation of contaminants through soil pores and/or bedrock fractures below ground, typically causing partial aquifer contamination. Generalised recharge is slower in areas where groundwater vulnerability is classified as low/moderate allowing for increased contaminant attenuation. This is the case as, in simple terms, vulnerability classifications measure the ease with which waters can move from the surface through the local soil and subsoil (DoEHLG/EPA/GSI, 1999). Where such ingress mechanisms are dominant, available prevention measures include drilling deeper wells and ensuring protection of the well shaft (with the use of appropriate casing/lining).

3) **Rapid (preferential) recharge**: this describes recharge in areas where soil pores are larger or where bedrock fractures form networks, and is associated with increased surface water/groundwater interactions (including via baseflow and interflow). Under these circumstances rapid transport through these preferential pathways prevents natural attenuation of contaminants as they percolate through the soil. This pathway is most common in areas of extreme groundwater vulnerability, for the reasons stated above; and in particular where karst aquifers are present as these are characterised by large fractures, sinkholes and underground caves through which water flows quickly receiving very little filtration. This is exacerbated during period of intense precipitation and flooding, due to an increase in the speed of contaminant transport through the subsoil (Hynds et al., 2012, 2014b; O'Dwyer et al., 2018, Andrade et al., 2018). Similarly, measures to prevent contaminant ingress via preferential flow includes drilling wells at greater depths and ensuring that the well shaft is appropriately protected.

4) **Direct surface ingress:** this mechanism refers to contaminant ingress which occurs directly at the supply wellhead. Concerns with this pathway are greater in regions where infiltration is limited, such as during periods of intense rainfall and/or flooding (which do not allow sufficient time for water to infiltrate) or in areas of low and moderate groundwater vulnerability (DoEHLG/EPA/GSI, 1999), as both circumstances lead to an increase in surface run-off. The rapid transport of contaminants through the surface or shallow topsoil does not allow for natural attenuation in these cases. To prevent instances of contamination, appropriate protection of the wellhead is critical.

As outlined above, contaminant ingress mechanisms to groundwater supplies hinge primarily on the presence/absence of certain well protective features (in particular mechanisms 2, 3 and 4), local soil and subsoil characteristics (e.g. local groundwater vulnerability based on local hydrogeology) and weather conditions (e.g. rainfall duration/intensity). These have been well documented in studies of *E. coli* (and other faecal microorganisms) presence in groundwater supplies (Hynds et al., 2014a; Murphy et al., 2017; Andrade et al., 2018; Reynolds et al., 2020; Chique et al., 2020b; Chique et al., 2020a). Relative consensus exists, however, that unsuitable well location and conditions (due to inappropriate construction and/or lack of maintenance) are the principal causes of faecal contamination ingress in Ireland (Bacci and Chapman, 2011; Hynds et al., 2012; Hynds et al., 2014b; Andrade et al., 2020) and abroad (Wallender et al., 2013; Stokdyk et al., 2020). As such, appropriate source protection can indeed, in many cases, prevent or decrease contamination, with a number of previous Irish studies of private well contamination having identified issues with liner integrity, lower liner clearance and lack of wellhead protection (e.g. wellhead below ground, inappropriately sealed cover, lack of vermin-proof cap) as significant linked with presence of *E. coli* (Bacci and Chapman, 2011; Hynds et al., 2012; Hynds et al., 2014b; Andrade et al., 2020).

It is also worth noting that wells constructed in karstic limestone areas, where groundwater is classified as extremely vulnerable (DoEHLG/EPA/GSI, 1999; GSI, 2020), have been consistently associated with higher rates of microbial contamination, such as *E. coli* and *Cryptosporidium* (O'Dwyer et al., 2014; O'Dwyer et al., 2018; Andrade et al., 2018; Chique et al., 2020). As such, extra precautions must be taken to protect and regularly test wells drilled in karst aquifer areas. Moreover, as increased rainfall periods lead to higher likelihood of *E. coli* presence in groundwater supplies (Bacci and Chapman, 2011; Hynds et al., 2014; O'Dwyer et al., 2018; O'Dwyer et al., 2020), well water tests should be undertaken preferably after these periods, as recommended by the EPA (EPA, 2017a), as well as after extreme weather events such as floods (Andrade et. al., 2018) to provide information under worst-case scenario conditions.

Where source protection is insufficient, as may be the case for pre-existing wells drilled in highly vulnerable areas and/or near potential sources of contamination, there are treatment options available which are effective in the removal of bacteria and most other microorganisms. The following are treatment solutions listed by the EPA (EPA, 2014b) for private wells:

> **Chemical (shock) disinfection**: This describes the process of dosing chemical disinfectants into the water to kill certain microorganisms present (EPA, 2011). In the case of private supplies, however, this method is not suitable for on-going treatment due to the low doses required and is instead used to disinfect the supply, sporadically or in response to

contamination (EPA, 2014b). This consists of pouring a chemical disinfectant (commonly chlorine) into the well, allowing it to stand for a number of hours and purging the well to remove the disinfectant (EPA, 2011). However, this practice is not recommended as a principal method to manage contamination, due to a common by-product of chlorine treatments: trihalomethanes (THMs). THMs may be formed when chlorine is added to water containing high levels of organic material and are classified as 'possibly carcinogenic' to humans (HSE, 2016). Moreover, this disinfection process is not suitable for treatment against *Cryptosporidium* (EPA, 2014b)

Ultraviolet (UV) light disinfection: UV disinfection is a non-chemical water treatment method that is effective, if used correctly, against most bacteria, viruses, and protozoa (including *Cryptosporidium*). The process relies on the use of germicidal wavelengths of UV light to inactivate the microorganisms present. It is important to note, however, that the water must be clear when entering the UV filter treatment (including low turbidity and low levels of iron and manganese), as particles presence can block the UV rays and prevent disinfection (EPA, 2014b). Thus, it is generally recommended that the water is filtered before going through this treatment.

Reverse osmosis: Reverse osmosis is another non-chemical treatment; it uses pressure to push the water through a semi-permeable membrane and filter out contaminants, such as bacteria, viruses, protozoa (including *Cryptosporidium*), nitrate and even certain types of arsenic. In this process, important minerals can also be removed, and it may be necessary to reintroduce them to the water after the treatment (EPA, 2014b). Due to elevated costs, this treatment is rarely used to manage microbial contamination alone.

As can be seen from the above descriptions, chlorination is only recommended as an immediate response to contamination in areas where levels of organic material are low, after the execution of this method the well water must be tested to ensure that is has returned to acceptable drinking standards; where this is not achieved an ongoing treatment option should be implemented. The two remaining technologies (i.e. UV lights and reverse osmosis) are appropriate for continual use, with suitable maintenance, to ensure contaminant-free water. Another method used where there is microbial contamination is boiling the water prior to consumption (EPA, 2014b); however this may not be the most practical option over long periods, particularly in larger establishments such as hotels. It is not possible to provide advice on which treatment is most appropriate as this will depend on factors specific to each SPS (or household well), such as budgetary constraints, pre-treatment needs, requirements for multiple contaminant removal (e.g. nitrate, arsenic, pesticides etc., as well as microorganisms), volume of water requiring treatment, etc.

In terms of UV disinfection and reverse osmosis systems, the location of treatment installation must also be considered, both can be installed either at the point-of-entry, or at the point-of-use:

> **At the point-of-entry:** In this option the entire establishment (e.g. entire house, restaurant, creche, hotel, etc.) is supplied with treated water. For that, treatment systems are typically installed shortly after the pressure tank (Yang et al., 2020).
>
> **At the point-of-use**: where this is the option chosen, treatment systems are typically installed for use at a single tap (usually in the kitchen), and are located below the sink (Yang et al., 2020).

In general, point-of-use treatments are a cost-effective option in establishments where the number of taps from which water is used for drinking/cooking are fewer, as it entails treatment of lower volumes of water. For other establishment, such as hotels and creches, having a point-of-entry treatment system may be the most suitable option.

5.2. Nitrate

Nitrate (NO_3) is a chemical compound that occurs naturally at low to moderate concentrations in the environment (≈ 2 mg/l) (Foster et al., 1982). It is widely known, however, that human activities can introduce nitrate in soil and groundwaters, raising concentrations to unsafe levels (i.e. > 50 mg/l) (EC, 1998), which becomes an issue when these resources are used for human an animal consumption. Historically, the main health concern linked to increased nitrate concentrations in drinking water has been methemoglobinemia, or “blue baby syndrome”, a potentially fatal condition that occurs in bottle-fed infants exposed to high levels of nitrate which prevents oxygen from being transported through the blood (Naser et al., 2007; Sadeq et al., 2008). Additionally, strong evidence exists which links continuous consumption of unsafe levels of nitrate with other adverse health effects such as colorectal cancer, thyroid disease, and neural tube defects (Ward et al., 2018). As such, it is paramount that nitrate levels in drinking groundwater resources and supplies are kept below the parametric value of 50 mg/l, as per the European Drinking Water Directive (EC, 1998).

Agricultural fertiliser applications, as both manure (organic) and synthetic (inorganic) fertilisers, are the primary sources of nitrate in the aquatic environment. In short, excessive or poorly-timed fertiliser application to crops and grazing fields results in incomplete adsorption of nitrate; as nitrate is highly soluble it can then leach through the soil and into ground and surface waters (Nolan, 2001). Unfortunately, as these practices are ubiquitous in rural areas of intense agricultural activity, high levels of nitrate in local surface and groundwater resources have become a serious issue. A recently published EPA water quality report (EPA, 2020a) highlights that nitrate concentrations have increased in 44% of rivers and 49% of groundwaters monitored in the period from 2013 to 2019, particularly in the south and south-east of the country where agricultural activities are more intense (EPA, 2020a). Other potential (point) sources of nitrate into groundwater (and surface water), albeit to a lesser extent, include leakage from livestock feedlots and waste storage, wastewater treatment discharge, faulty septic tank systems, certain industrial wastes, and farmyard drains (Jensen et al., 2014; Harrison et al., 2019). As such, changes in land use and agricultural management can have a significant impact in minimizing nitrate loading to the environment and, consequently, to surface and groundwater resources.

Current regulations mandated by the European Commission Nitrates Directive has set restrictions to manure application on crops of 170 kg of nitrogen per hectare per year for regions that are prone to nitrate leaching (European Commission, 1991). However, this may not be sufficient to lower contamination rates to desirable levels. Key additional agricultural management practices which are beneficial in preventing nitrate surplus and subsequent issues with local surface and groundwater quality include (1) ensuring bespoke fertiliser application rates relative to demand (Sahoo et al., 2016), (2) ensuring appropriate manure storage conditions (Sahoo et al., 2016), and, where possible, (3) reducing recharge rates under agricultural activities during crop's (including grass/grazing land) growing season (Rosenstock et al., 2014; Baram et al., 2016). Moreover, in specific locations where the potential for nitrate leaching into groundwater is high (e.g. presence of coarser soils, fractured bedrocks and karst aquifers) (i.e. high/extreme groundwater vulnerability sites; DoEHLG/EPA/GSI, 1999), further regulatory restrictions may be needed to prevent instances of contamination (Sahoo et al., 2016).

1) **Fertiliser application relative to demand**: excess fertiliser application is the primary cause of nitrate leaching into nearby surface and groundwater bodies (Nolan, 2001). These practices are particularly common where manure produced on a farm surpasses crop's demands (Jarvis, 1993; Nolan, 2001; Sahoo et al., 2016). To ensure optimum application of fertiliser with minimum nutrient surplus, well-timed soil testing should be employed in combination with accurate translation of test results into appropriate nutrient management practices (Buckley et al., 2015; Kelly er al., 2016). Weather conditions must also be considered. For example, regulations in many countries limit fertiliser application at certain times of the year (e.g. immediately before, during, and after high intensity rainfall and during floods) (Sahoo et al., 2016).

2) **Appropriate manure storage:** appropriate protocols for manure storage and management are crucial to protect water resources from nitrate contamination. Manure storage must be located preferably downslope and at a certain setback distance from drinking water sources (including drinking wells) (Sahoo et al., 2016); in Ireland, manure storage must be at least 250 m away from SPSs (EU, 2017a). A compacted soil cover must also be employed to seal the site where manure is being stored, this indirectly facilitates microbial conversion of nitrate to nitrogen gas, reducing nitrate levels which may leach into groundwater (Sahoo et al., 2016). When planning manure storage, local hydrogeology and water table depth must also be considered. In the case of karst and other extreme groundwater vulnerability areas, for example, manure storage facilities should be constructed utilizing a rigid material (e.g. concrete or steel) to prevent seepage into the local groundwater and setback distances from water supplies should be raised (Sahoo et al., 2016). Practices such as regularly cleaning animal grazing areas and following appropriate farmyard abandonment protocols (i.e. replacing all manured soils with new soil materials and planting crops that require high levels of nitrogen) can also reduce the amount of manure in the runoff and infiltrated waters leaving the agricultural fields minimising contamination of nearby waters (Sahoo et al., 2016).
3) **Reduced recharge rates under agricultural activities**: lower recharge rates increase nitrate travel times in the unsaturated zone (i.e. the soil layers located above the water table) which helps control nitrate contamination of groundwaters (Baram et al., 2016). Reduced recharge rates in farmed areas can be added as part of nutrient management plans by implementing water diversion methods to reduce the amount of freshwater entering farmed areas. Water diversion can be employed using small terraces, roof gutters, earthen ridges, etc. to redirect rainwater away from agricultural fields (Sahoo et al., 2016). In addition to those, vegetation filter strips (also known as buffer strips) can also be introduced to control pollutants in the agricultural runoff from reaching surface and groundwater bodies (Clausen and Meals, 1989; Sahoo et al., 2016).

With regards to the influence of extreme weather conditions, such as intense precipitation and flooding, their impact in lowering or raising groundwater nitrate concentrations are highly dependent on local soil and overall hydrogeological characteristics. In general, prolonged and/or intense rainfall can cause an increase in nitrogen leaching and runoff from agricultural fields and into groundwater supplies; however, it may also cause the dilution of contaminants already present in the supply or the aquifer. In Ireland, a study in the south-west of Ireland found that effective rainfall was not a significant parameter in predicting groundwater nitrate and attributed this to relatively low and uniform rainfall during the studied period (Tedd et al., 2014), with another study in the south-east of the country reporting similar results (Baily et al., 2010). As such, water test results performed during atypical or extreme weather conditions, such as uncharacteristically intense rainfall or drought conditions, are advised and must be interpreted with care.

In terms of protection at source, a similar approach to the one used to prevent faecal microorganism contamination can be employed - i.e. ensuring that the supply is constructed at sufficient distances from potential point and nonpoint (diffuse) sources of nitrate (see **Table 6**). In turn, fertiliser application and location of other potential nitrate sources must be restricted, where pre-existing groundwater supplies are present, to comply with minimum setback distances. Indeed, two studies undertaken in Ireland have identified that groundwaters at increased distances to point and nonpoint sources of nitrate display lower levels of contamination (Fenton et al., 2009; Baily et al., 2011). Moreover, appropriate wellhead and well shaft protection must be employed to prevent nitrate contamination via direct ingress and groundwater recharge (see the potential contaminant ingress mechanisms described in Section 5.1). It is also well established that in the case of nitrate occurrence in groundwater supplies due to contaminated aquifers (see again Section 5.1) these are, in general, more prominent in shallow wells (i.e. less than 30 meters below ground level; Nolan, 2001; Babiker et al., 2004; Bohlke et al., 2007; Baily et al., 2011), as nitrate concentrations in the subsurface decrease with depth (Nolan et al., 2002). Thus, it is recommended that deeper wells are used in areas of intense livestock and agricultural activity. However, care must be employed where there is risk of groundwater quality deterioration with depth due to other contaminants, such as arsenic (see Section 5.3).

In cases where source protection is not sufficient to prevent nitrate contamination, which may occur where contamination is coming from the underlaying aquifer, mentioned above, and alternative water supplies are available (i.e. another drilled well, a local Group Water Scheme or public mains) other management strategies can be employed, such as the use of blending or the decision to abandon the well, which are the two nontreatment-based options outlined below:

Blending: This option refers to the dilution of nitrate contaminated waters with uncontaminated or low-nitrate waters from an alternative supply (HSE/EPA, 2010). Where feasible, blending is a simple cost-effective alternative to treatment that avoids issues with the disposal of nitrate-rich by-products. However, disadvantages include the investment costs of securing an alternative source (e.g. drilling another well, getting connected to mains water, or joining a GWS) and continuously monitoring nitrate levels to ensure appropriate blending ratios (Jensen et al., 2014). Despite lack of nitrate removal this management strategy is sometimes referred to as treatment.

Well abandonment: where contamination is persistently found at extreme concentrations, an owner may choose to no longer abstract water from the supply. If this option is chosen, it is important that well owners are aware of the importance of following appropriate protocols to prevent the discarded supply from acting as and entry point of contamination directly into the aquifer and other nearby supplies. Protocols for abandonment may include the covering, sealing and/or plugging of the well (IGI, 2007; Jensen et al., 2014). This option is different to well destruction, where the supply is filled and, as such, cannot be re-activated.

In terms of treatment options available to deal with nitrate contamination, these are reverse osmosis and ion exchange (HSE/EPA, 2010; EPA, 2014b), both are described below:

Reverse osmosis: This option has already been outlined in the previous section as a treatment for removal of microbial contaminants (including *Cryptosporidium*) and is also effective in the removal of nitrate. Briefly, this systems employs the pressurised passage of water through a semi-permeable membrane which filters out unwanted (and even some wanted) components (EPA, 2020b). Reverse osmosis can also be used to treat waters with an array of other contaminants such as arsenic, sodium, chloride, nickel, fluoride, asbestos, and certain pesticides (Malaeb and Ayoub, 2011; Jensen et al., 2014). This information is particularly relevant as, similarly to nitrate, some of these contaminants can originate from intense agricultural activities.

Water softener/Ion exchange: Similarly to reverse osmosis, ion exchange systems can also address multiple chemical contaminants, including arsenic, nickel, selenium, chromium, and uranium (Jensen et al., 2014). However this is rarely used for nitrate removal alone. In this system, water passes through an ion exchange resin, where the nitrate is held and replaced with chloride ions (Jensen et al., 2014).

Prior to choosing the appropriate treatment option, local groundwater must be fully characterised. This is the case because the presence of certain components can require pre- and/or post-treatment, or even render an option unfeasible, as is the case for sulphate-rich waters (common in peat areas) treated with ion exchange systems (Jensen et al., 2014).

Regardless of the treatment system chosen, its location within the water distribution network must also be considered (i.e. at the point-of-entry or at the point-of-use, see Section 5.1) and it will be necessary to arrange appropriate disposal of the waste generated, particularly as it may contain higher concentrations of carcinogen compounds such as arsenic and uranium. It is important to note also, that unlike microbial contamination, boiling cannot be used as an alternative to treatment installation in this case. Indeed, evaporation will lead to higher concentrations of nitrate in the remaining water (HSE/EPA, 2010).

5.3. Arsenic

Arsenic is a toxic metalloid and a known carcinogen, with chronic exposure to unsafe concentrations (i.e. > 10 μg/l; EC, 1998) shown to increase the likelihood of developing lung, bladder, skin, kidney, liver, and prostate cancers (International Agency for Research on Cancer, 2016). In addition, long-term consumption/inhalation of arsenic has also been linked to the onset of diabetes, cardiovascular disease, and neurodevelopmental impairments in foetuses (Moon et al., 2012; Tyler et al., 2014). Acute exposure to high concentrations of arsenic (i.e. arsenic poisoning) can also trigger adverse health effects, such as abdominal pain, diarrhoea, and vomiting (World Health Organisation, 2018).

In the environment, arsenic is classified as a geogenic contaminant, meaning it can occur naturally in soil and groundwaters under certain hydrogeological conditions; most commonly in the ionic forms arsenite (AsIIIO33-) and arsenate (AsVO43-) which are both highly toxic (Fendorf et al., 2010). This means that groundwater supply contamination is due to arsenic presence in the aquifer (see the first ingress mechanism in Section 5.1), and thus cannot be managed through source protection measures. The occurrence of arsenic in the subsurface is highly dependent on the local geology/lithology and, unlike the other contaminants described in this report, deeper groundwater wells may be at greater risk of contamination (McGrory et al., 2017). As such, it is important to identify areas in which the risk of arsenic in groundwater is higher and employ the assistance of geologists/hydrogeologists when drilling wells to ensure, where possible, that exposure to elevated concentrations of arsenic is avoided. Annual water tests for arsenic are also strongly advised in regions characterised by high geogenic arsenic concentrations.

Where necessary, arsenic-contaminated water may still be used for human consumption with the use of appropriate treatment systems. The two available options for this purpose are reverse osmosis and ion exchange systems (see Section 5.2 for detailed descriptions, as these are also suitable for nitrate removal). Treatment selection must be based on a full characterisation of the supplied water, with identification of baseline concentrations and the ionic form (or forms) of arsenic present. This is important as arsenite and arsenate are associated with different arsenic removal rates (Yang et al., 2020) and the need for pre- and/or post-treatment (Sargent-Michaud et al., 2006; Litter et al., 2019) may also vary depending on the type of treatment. In terms of treatment placement within the water network for arsenic removal it is advised that, regardless of the option chosen, these are installed at the point-of-entry (typically located shortly after the water pressure tank), so that the entire establishment is supplied with treated water (Yang et al., 2020). This is the case as point-of-use systems (i.e. those installed for use at a single tap) may result in arsenic exposure at other (untreated) outlets and have been associated with higher failure rates by previous studies (Yang et al., 2020). It is also strongly recommended that the chosen arsenic treatment system is installed and maintained by vendors or qualified personnel, as under their professional care arsenic removal is less likely to fail (Yang et al., 2020).

In cases where arsenic treatment solutions are not viable, owners may choose to stop the supply's activities. If this option is chosen, it is paramount that the well is appropriately discarded, to prevent it from becoming an entry point for other types of contamination into the aquifer. This may involve the covering, sealing and/or plugging of the supply (Jensen et al., 2014; IGI, 2007).

5.4. Lead and Copper

Study results reported in **Table 4** show that just 0.7% of groundwater monitoring stations in Ireland have exceeded permissible concentrations of lead at least once from 2014 to 2019 and none have exceeded MPCs of copper. However, both were found in over 1% of SPSs nationally during the same period. This finding supports the hypothesis present in EPA reports (EPA, 2015) that internal pipes and plumbing are the principal sources of lead and copper in drinking water.

Of the two contaminants, lead is particularly hazardous to human health as continuous ingestion can cause serious adverse effects in foetuses, infants, and young children. In Ireland, properties built before the 1980s were still allowed to utilise lead pipework or lead-containing fixtures and solders, thus it is paramount that these are surveyed by current owners to prevent lead exposure through drinking water (HSE/EPA, 2013; Irish Water, 2017). This can be achieved with the assistance of a qualified plumber or by testing the water for lead (HSE/EPA, 2013). Where this issue is identified it is recommended that the pipes and other plumbing made of lead (or copper) be removed and replaced with alternative materials.

5.5. Summary of source protection and management recommendations

The principal source protection and management practices recommended for the prevention/management of contamination according to the current study (with emphasis on *key contaminants*) are summarised in

Table 7 and **Table 8**, respectively. As shown in

Table 7, most of the recommendations are already in place, however these are not always widely available, as is the case for recommendations present only in IGI guidelines. Moreover, changes to certain regulations are recommended, such as an increase in current minimum setback distances to potential sources of contamination (e.g. farming activities and domestic wastewater treatment systems) to account for extreme weather conditions, which are predicted to increase due to climate change (Pall et al., 2011; Arnell and Gosling, 2016). It is advised that where not already present, recommendations should be incorporated as part of updated well stewardship guidelines, which is the case for measures iii, vii, x and xi (

Table 7).

In addition to absence of specific evidence-based recommendations, recent EPA reports also highlight insufficient enforcement of current guidelines by LAs (EPA, 2015; 2017b; 2020b; 2021), with many SPS remaining unregistered and up to 27% of registered SPSs lacking annual monitoring. This is likely due to insufficient resources within LAs, as well as a governance structure which is ill-equipped to deal with the complexities of well stewardship promotion and enforcement (Mooney et al., 2020). As such, a key recommendation of this research is that a specific governance organisation is formed to deal specifically with SPS-related issues nationally, and to work alongside LAs at the regional and community levels. For this, a similar structure to that employed by the NFGWS, which works closely with Group Water Schemes across the country, may be utilised. Based on the findings from this section the responsibilities of this new organisation should include (1) registering all SPSs in the country; (2) updating current available guidelines (in line with evidence-based recommendations), (3) producing hotspot maps for naturally occurring groundwater contaminants (e.g. arsenic) alongside specific well stewardship guidance for these high-risk areas, and (4) enforcing all current (and updated) guidelines and regulations.

Table 7: Direct and indirect source protection measures available to small private (groundwater) supplies and private household wells in the Republic of Ireland.

Source protection measures to prevent contamination	Reasons for implementation	Key contaminants prevented	Present in current guidelines
1. Supply location and its surroundings			
i. Supplies should be located as far as possible from potential sources of contamination, in accordance with minimum setback distances	To allow for sufficient contaminant attenuation to take place and lower the likelihood of a supply becoming contaminated	*E. coli* and nitrate	Yes (however minimum setback distances may need to be increased)
ii. Supplies should be in a mounded area, with ground sloping away from it.	To prevent contamination via direct surface ingress, as the slope can prevent runoff of contaminated surface from reaching the supply's wellhead.	*E. coli* and nitrate	Yes
iii. The area surrounding a supply (i.e. within 10 meters of it) should be, grassed, fenced (to avoid animal access), and kept free of debris.	To prevent contamination via direct surface ingress, as cleared grassed areas are less conducive to surface run-off which may carry contaminants into the supply.	*E. coli* and nitrate	No
2. Construction features			
iv. Supply chambers should (ideally) be made of concrete and constructed above ground, with walls and floor kept dry, clean, and crack-free. Annual inspections are recommended.	To protect the supply's wellhead from contamination via direct surface ingress.	*E. coli* and nitrate	Yes (however this is only mentioned in the IGI guidelines; IGI, 2007)
v. Supplies should be capped (with vermin-proof cap) and appropriately sealed.	To protect the supply's wellhead from contamination via surface ingress.	*E. coli* and nitrate	Yes
vi. Supplies should have a casing made of steel or PVC, which is elevated by at least 30 cm above the chamber floor (IGI, 2007) and kept crack-free.	To prevent contamination via direct surface ingress and recharge.	*E. coli* and nitrate	Yes (however this is only mentioned in the IGI guidelines; IGI, 2007)
vii. Supply chambers should be appropriately covered and sealed between inspections.	To further protect the supply's wellhead from contamination via surface ingress.	*E. coli* and nitrate	No
3. Drilling process			
viii. Deeper wells are recommended to prevent against source contamination with anthropogenic contaminants such as *E. coli* and nitrate, however care is advised where there is risk of geogenic contamination (e.g. arsenic).	To prevent contamination via groundwater recharge and shallow contaminated aquifers.	*E. coli* and nitrate	No
ix. Employ the assistance of geologists/hydrogeologists when drilling wells in areas where there is risk of geogenic contamination (e.g. arsenic)	To, where possible, eliminate or reduce the need for treatment by preventing supplies from obtaining their water from a contaminant-rich strata.	Arsenic	No
4. Continuous maintenance			
x. Test supply's water annually, preferably following periods of intense rainfall and/or extreme weather events, and at least twice per year for *E.coli*. Tests for hazardous chemicals must be included if the supply is located in a known hotspot area.	To monitor the water quality at source and inform owners of further source protection and/or treatment needs.	All	Partially (extreme weather events and increased testing in hotspot areas not currently mentioned)
xi. Supply chamber, its surrounding area and any treatment systems (where present) must be inspected/serviced at least annually.	To identify potential issues at early stages and take the necessary measures.	All	No
5. External management practices			

xii. Implement appropriate farm and septic tank management (i.e. follow regulations/advice in Good Agricultural Practices for the Protection of Waters document (EU, 2017a) and Code of Practice for Wastewater Treatment Systems for Single Houses (EPA, 2010)	To lower the risk of contamination from potential nearby sources.	*E. coli* and nitrate	Yes

Table 8: Contaminant management practices available to small private supplies and private household wells in the Republic of Ireland

Contamination management	Further descriptions	*Key contaminants* managed
1. Well abandonment	Appropriate abandonment protocols may include the covering, sealing and/or plugging of the supply (IGI, 2007; Jensen et al., 2014).	All anthropogenic contaminants (*E. coli* and nitrate)
2. Boiling the water before consumption	Implementing boiling of the water prior to consumption can be used to deal with microbial contamination (EPA, 2014b). However, this practice is **not** recommended where there is risk of chemical contamination (HSE/EPA, 2010).	*E. coli* *(Not recommended where chemical contamination is suspected)*
3. Shock chlorination	This management options may be used sporadically to deal with microbial contamination. However it is not recommended where the levels of organic material are high, due to a common by-product of chlorine treatments: trihalomethanes (THMs), which are classified as 'possibly carcinogenic' to humans (HSE, 2016). Moreover, this disinfection process is not suitable for treatment against Cryptosporidium (EPA, 2014b)	*E. coli* *(Not recommended where levels of organic material in local groundwater are high)*
4. Blending	This management option refers to the dilution of nitrate contaminated waters with uncontaminated or low-nitrate waters from an alternative supply (HSE/EPA, 2010).	nitrate
5. UV light disinfection	This treatment relies on the use of germicidal wavelengths of UV light to inactivate the microorganisms present in the water. For this, the water must be filtered before going through the treatment.	*E. coli*
6. Water softener/Ion exchange treatment	In this treatment system water passes through an ion exchange resin, which traps an array of contaminants removing them from the water.	Nitrate and arsenic
7. Reverse osmosis treatment	This treatment uses pressure to force the water through a semi-permeable membrane, filtering out an array of contaminants.	*E. coli,* nitrate and arsenic,

6. Communicating protective measures

In Ireland, limited “top-down” management of SPSs places significant burden of supply protection and management on owners themselves. Thus, risk communication strategies are indispensable as a means to motivate behavioural changes and reduce water quality issues (Fox et al., 2016; Mooney et al., 2020). Historical underuse of communication theories and behavioural change strategies, however, coupled with a noted absence of multidisciplinary (e.g. educational, communication, science, engineering) expertise in the development and implementation of outreach efforts has hindered their success (Mooney et al., 2020; EPA, 2020b). As such, significant changes are needed in the design of future campaigns to achieve desired water quality improvements; from the generation of appropriate messages that motivate behavioural change to the use of dissemination methods which maximise supply owners’ exposure and engagement.

6.1. Message development

The primary goal of communication efforts aimed at private supply owners is to improve water quality, ultimately protecting the health of consumers through behavioural change. To do this, barriers to desired behaviours must be identified and targeted as part of outreach messages (Morris et al., 2016; Mooney et al., 2020). Below are the principal barriers to well stewardship described in the literature, as well as tools and methodologies that can be used to overcome them.

Lack of knowledge/awareness: Knowledge (or lack thereof) is one of the primary barriers to any behaviour uptake (Morris et al., 2016), as individuals who do not understand the need for a particular behaviour or how to engage with it are unlikely to change (Imgrund et al., 2011). In the context of well stewardship behaviours by supply owners, recurring inaccurate beliefs (derived from insufficient knowledge, poor advice, or conflicting information) must be identified and addressed. For example, many well owners rely on incorrect treatment systems to remove harmful contaminants or believe they can detect contamination without needing to test the water (based on changes in taste, smell, and/or colour) (Roche et al., 2013; Flanagan et al., 2015a; Morris et al., 2016 Musacchio et al., 2021). Thus, communication messages to supply owners must introduce clear and concise information supporting the need for change in current source protection and other well stewardship behaviours, including how groundwater contamination occurs, the health issues which may arise from consumption of contaminated water, how treatment systems may be used, etc. Other ways in which knowledge barriers may hinder behavioural change is related to lack of specific (practical) information to support source-protection

(Mooney et al., 2019). These may include how to collect a water sample and where to get it tested, how to interpret results and choose appropriate treatment system(s), which features must be present to protect the water at the source, how often wells and treatment systems must be inspected/serviced, etc. (Pyrch 1999; Jones et al., 2005; MacDonald Gibson et al., 2017). A recent study (Mooney et al., 2020) reports that the absence of step-by-step well maintenance information, for example, may be a longstanding impediment to appropriate maintenance practices by Irish well owners. It is also important to acknowledge that knowledge/awareness barriers can be exacerbated by flawed communication strategies and lack of cooperation between different communicators (see Section 6.2 for more information on how to avoid this), which ultimately lead to the dissemination of conflicting information (Meijers and Rutjens, 2014; Nagler, 2014; Morris et al., 2016). As such, consulting with educators and communication experts is advised, particularly when producing messages that modify current recommendations or challenge mainstream beliefs, as these may be met with confusion and resistance (Hanchett et al., 2002; Nagler, 2014).

Risk perception: For an individual to take protective action (i.e. change a behaviour) to prevent health risks, as is the case with well stewardship and source protection practices, they must first perceive these risks as being sufficiently serious and likely to occur (Morris et al., 2016). It is widely reported in the literature that supply owners tend to underestimate risks of contamination (Schuitema et al., 2019). Thus, it is important to actively target risk perception as part of communication efforts rather than wait for a natural surge (e.g. following contamination or serious adverse health issues). Well-known methodologies to achieve this are fear appeals, in which individuals are provided with information that makes them feel at risk (Nestler and Egloff, 2010; Morales et al., 2012), however this must be coupled with high-efficacy messages showing people how to protect themselves from harm (Witte and Allen, 2000). In the case of well stewardship promotion, this can be done by reminding well owners of the tangible risks (i.e. adverse health effects, financial costs which could arise from inaction) associated with certain contaminants and highlighting contamination issues locally, as individuals are more likely to engage with protective behaviours if they feel personally threatened (Imgrund et al., 2011; Flanagan et al., 2015) or reside in known contamination hotspots (Pyrch 1999; Jones et al., 2006). This approach has been shown to yield successful results; however its overuse may discourage engagement by those who prefer to avoid unpleasant emotions (Witte and Allen, 2000; Nestler and Egloff, 2010). It must also be acknowledged that low risk perception by supply owners may have different origins, such as illusion of control (i.e. when people perceive themselves to be more in control of a situation than they actually are; Hooks et al., 2019) and previous experiences (e.g. drinking from the same source for years without any perceived health problem, previous well water test results showing no contamination, etc; Doria, 2010; Fitzpatrick-Lewis et al., 2010). Where that is the case, risk perception may be targeted by providing appropriate information regarding long-term contamination effects (such as is the case for arsenic and other carcinogen contaminants), and the transitory nature of groundwater contamination (i.e. well tests are only a 'snap-shot' of water quality conditions at the time of sampling, and regular testing is the only way to ensure continuous drinking water quality).

Self-efficacy: Self-efficacy refers to a person's belief in their ability to deal with and manage prospective situations (Mosler, 2012). In the context of water supply management these may relate to a persons' perceived ability (belief) to appropriately interpret and respond to well water test results, or remembering to engage with protective behaviours at desirable intervals (e.g. getting the well water tested, servicing treatment systems or inspecting the supply annually). While these may seem minor barriers to some, they can represent considerable challenges to others (Pyrch, 1999), with communication experts believing that self-determined efficacy in executing maintenance actions can strongly influence a person's willingness to adopt desired behaviours (Mooney et al., 2020). This may be addressed via dissemination of practical information related to well stewardship (e.g. how to prevent contamination at source, how to test the water and interpret results, how to select appropriate treatment, etc.). It is also reported that self-efficacy and control can give people a false sense of security (Schuitema et al., 2019). Owners may think that they are in control of contamination risks when, in fact, they are not; in those cases, promoting 'How often'/'how frequent' messages become as important as 'how tos'. Moreover, where possible, testing and maintenance reminders can be sent to registered SPS owners. These eliminate the need for individuals to rely on self-regulation, until the desired practices become habitual (Jones et al., 2005; Kreutzwiser et al., 2011; MacDonald Gibson et al., 2017).

Social norms: Longstanding social norms are amongst the top three barriers to well stewardship (alongside knowledge and financial cost) identified by fifty national and international experts in communications, engineering/science, policy, and risk assessment interviewed in a study by Mooney et al. (2020). Social norms refer to established conventions or values, with cultural practices at the household level having a significant role in undertaking behaviours towards water supply protection (Morris et al., 2016; Mooney et al., 2020). An example is the widespread view of groundwater as a 'pure' (i.e. chemical-free) and universally safe resource. To overcome such barriers, community-based interventions (see Section 6.2) may be needed which focus on demonstrating tangible risks and benefits to behaviour uptake by means of family-oriented messages and health tailored information (Mooney et al., 2020). Community-level dissemination is recommended in this case as, in general, people in smaller communities may be reluctant to engage with government-mandated guidance to do with their water supply.

(In)Convenience: There are many inconveniences (large and small) associated with appropriate source protection and well stewardship behaviours (Schultz, 2014; Morris et al., 2016). These may be long distances to testing facilities, difficulties in identifying appropriate treatment and treatment system providers (where needed), time-commitment involved in testing and inspecting the supply/treatment system regularly, effort involved in seeking appropriate response to sporadic weather events such as floods and droughts, among others. Thus, it is important that communication messages also provide practical information, such as easy-to-find lists of reputable water testing facilities, and treatment system providers, step-by-step guides to interpreting well water tests and selecting adequate treatment systems, and having a point of contact for supply owners in case issues arise. The objective with these communication tools is to make behaviour change as easy and painless as possible, as even relatively small practical barriers can lead to inaction (Morris et al., 2016).

Financial cost: As previously acknowledged, the monetary cost associated with appropriate supply management remains one of the principal barriers to engagement with protective behaviours (Jones et al., 2005; Morris et al., 2016; MacDonald Gibson et al., 2017; Mooney et el., 2020). Indeed, most desired behaviours (i.e. regular water testing, treatment installation and maintenance, and upgrades to an existing supply, where appropriate) require a monetary investment. In Ireland, grants are available for household wells (but not SPSs) to update the source and/or install treatment (more information at https://www.gov.ie/en/publication/1d9d8-private-wells/) as an effort to overcome this barrier, however under-subscription indicates that this may not be sufficiently advertised. No financial aid is currently available in Ireland which subsidises the costs of well water tests, or treatment installation and improvements to SPSs.

As shown above, there are many inherent complexities associated with the development of effective messages to instil behaviour change among private supply owners. This stems from the fact that multiple obstacles may be hindering, delaying, or preventing behaviour uptake (Morris et al., 2016; Mooney et al., 2020). Thus, separate massages may be needed (potentially at separate communication stages and aimed at different audiences) to target them all (Morris et al., 2016; Mooney et al., 2020). A few suggested communication materials and messages are described in **Table 9** which may be used to motivate behaviour change. However care must be exercised to avoid exacerbating certain cognitive or practical barriers, such as might occur with the overuse of fear appeals (Jones et al., 2006; Nestler and Egloff, 2010). To prevent this, message development with the assistance of education and communication experts is advised. Indeed, the participation of communication and educators in message development has been significantly linked with success in health interventions aimed at private well owners internationally (Mooney et al., 2019).

Table 9: Suggested communication materials as part of cohesive communication strategies to motivate well stewardship in the Republic of Ireland.

Communication materials [a]	Rationale	Targeted Barriers
Materials aimed at supply owners		
1. Risks of contamination to groundwater supplies: Include information on general groundwater contamination, what facilitates it, the main health risks which can be caused by it, and (briefly) what can be done to prevent it.	To bring awareness to current and future supply owners of potential issues due to lack of well stewardship	Knowledge/ awareness and social norm [b]
2. Step-by-step guide to well construction: Include an introduction on the importance of appropriate construction to safeguard family health followed by detailed information regarding well location, well depth and all necessary protective features. Bring awareness to available grants and link to a regularly updated webpage with registered well drillers	To promote appropriate construction of new supplies, and inform current and future supply owners of necessary protective features.	Knowledge/awareness, self-efficacy, (in)convenience, financial cost and social norm [b]
3. Step-by-step guide to supply maintenance: Include an introduction on the importance of appropriate maintenance to safeguard family health followed by detailed information regarding supply maintenance. Bring awareness to updated webpage where registered service providers are listed	To promote appropriate supply maintenance	Knowledge/awareness, self-efficacy, (in)convenience and social norm [b]
4. Step-by-step guide to water test interpretation and treatment selection/maintenance: Include an introduction on the importance of installing appropriate treatment, where needed, to safeguard family health followed by detailed information on how to interpret water test results and use them to identify treatment needs, information regarding treatment maintenance needs and approximate monetary cost should also be present. Bring awareness to available grants and links to regularly updated webpage where registered treatment providers are listed	To promote appropriate treatment selection and its maintenance	Knowledge/awareness, self-efficacy, (in)convenience, financial cost and social norm [b]
5. Step-by-step guide to supply protection during/following extreme events: Include an introduction on the potential impacts of extreme weather events on water supplies and consumers health, followed by detailed information on how to protect the supply during and following these events	To prevent contamination and potential illness outbreaks following extreme weather events.	Knowledge/awareness, risk perception, self-efficacy, (in)convenience and social norm [b]

6. Lists of registered professionals and service providers: include the contact of registered well drillers, water testing facilities, treatment providers, etc.	To facilitate the pursuit of services and encourage the use of reputable professionals and companies	Knowledge/awareness, self-efficacy, (in)convenience and social norm [b]
Materials aimed at other stakeholders (i.e. public and private organisations, and service providers)		
7. Step-by-step guide to well stewardship dissemination: Include an introduction on the importance of appropriate communication with supply owners, followed by detailed description of the information which should be provided to well owners and the tools and methodologies which should be used in disseminating it	To support cooperation between stakeholders and communicators as part of cohesive dissemination campaigns	-

[a] messages should be produced using attractive graphics and simple/concise language; [b] social norms may be targeted when message is disseminated at the community level using two-way engagement approaches (see table 11)

6.2. Dissemination strategy

It is widely agreed on by experts in the field of health communication, policy, and risk assessments that multi-level dissemination approaches (i.e. message framing) are most effective at motivating behaviour change amongst private supply owners (Mooney et al., 2020). Indeed, as different individuals prefer different methods of communication, providing information through multiple channels will increase the likelihood of reaching and appealing to more supply owners (Fitzgibbon et al., 2007; Fitzpatrick-Lewis et al., 2010; Campo et al., 2013; Morris et al, 2016). Moreover, different levels of dissemination have been shown to achieve varying degrees of success in targeting specific behavioural barriers (see Section 6.1) as part of outreach campaigns (Mooney et al., 2019) while being insufficient to promote behavioural change on their own (Muene et al., 2019).

Dissemination at the national level: Traditional broadcast media (e.g. radio, television, newspapers) and the internet (e.g. governmental websites, social media, etc.) are the main channels used for message distribution at the national level due to their broad reach (Morris et al., 2016; Mooney et al., 2020). However, it has been noted by Irish experts in the field that active traditional and social media advertisements are under-used in Ireland (Mooney et al., 2020) despite having been shown to be successful when used to increase supply owners' knowledge and raising awareness (Figueroa and Kincaid, 2010; Lundgren and McMakin, 2013; Mooney et al., 2019). Mass media is a powerful tool in communication efforts; however success rates will be dependent on the quality of the content being disseminated. As such, educators and communication experts should be employed to produce informational, motivational and engaging communication materials (Mooney et al., 2020). More targeted approaches are also available at the national level, such as direct mailing (which are possible in the case of registered SPSs) to reach those that are not actively seeking information (Renaud et al., 2011) and send reminders (MacDonald Gibson et al., 2017).

Dissemination at the regional level: The internet and traditional media are means of mass communication that can also be implemented at the regional level (i.e. local radio stations, newspapers, webpages, social media platforms, etc.). Previous reviews have identified regional outreach to be less successful than national level efforts (Mooney et al., 2019). However, there is value in combining national and regional level avenues as part as of a cohesive dissemination campaign aimed at promoting awareness (Mooney et al., 2020), particularly in the communication of hotspots of contamination and/or waterborne infection. Direct mailing is also available, and perhaps more so, as a communication resource at the regional level, being listed as a necessary practice by field experts in the US (MacDonald Gibson et al., 2017). For these and all other communication materials, it is important to highlight once again the importance of well-produced and engaging messages to prevent the generation of confusing or conflicting information (Meijers and Rutjens, 2014; Nagler, 2014).

Dissemination at the local/community level: Community-based communication strategies are traditionally better placed to engage with private supply owners and users on a more targeted and face-to-face basis, yielding higher success rates in the promotion of behavioural change (Morris et al., 2016; Mooney et al., 2019). For this, however, collaborative efforts are needed between national/regional and local-level stakeholders to better understand local needs and where there may me resistance to change (Morris et al., 2016; Mooney et al., 2020). Moreover, community members tend to be more receptive towards (and likely to follow) recommendations from familiar and locally respected groups (Pyrch 1999; Maslia et al., 2005; Balamurugan et al., 2007; Morris et al., 2016; Henry and Suk, 2018). Engagement with locally-based organisations may be facilitated with the assistance of educational and research body coordinators, particularly as their involvement in communication efforts have been associated with higher behaviour uptake (Mooney et al., 2019). Workshops and campaigns targeting source remediation, safe source installation and the importance of regularly testing the water are just some well-known examples where this methodology has been successfully implemented (McCann and Gold, 2012; Mooney et al., 2019). Frequently recommended communication activities at the local level include workshops, community meetings, event booths at local events, school programmes and citizen science initiatives (Franz, 2014; Morris et al., 2016; Mooney et al., 2019; Mooney et al., 2020). At the community level, long-term communication approaches are crucial to promote sustainable social norm changes and desired behaviour uptake, as well as to inspire trust in the message and its disseminators (Mooney et al., 2020). The well-documented efficacy and importance of groundwater education initiatives at primary and secondary school levels are a key example of well stewardship motivation into the future and long-term cultural changes within a community (Thornton and Leahy, 2012; Mooney et al., 2020).

Given the three communication levels available and based on currently literature, it is strongly recommended that outreach efforts incorporate a combination of large-scale media-based campaigns and face-to-face locally-focused interventions (Mooney et al., 2020). As mentioned previously, certain dissemination outlets are historically more successful at targeting specific barriers, with national-level dissemination recommended for raising awareness while community level events are recommended to promote behavioural change (Mooney et al., 2019).

As with any intervention campaign, it is also crucial to incorporate periodic (annual/biannual) evaluations to gauge target audience's response, knowledge gaps, stewardship uptake, and general feedback. Evaluations can be carried out via surveys (at the national/regional level) and/or focus groups (at the community level). The findings from these can then be used not only to measure progress but also to improve subsequent messages, and dissemination/engagement mechanisms.

A few available dissemination tools which may be used in the Irish context are suggested in **Table 10**.

Table 10: Communication tools suggested which may be implemented as part of cohesive communication strategies in the Republic of Ireland.

Communication tools	Dissemination level	Rationale
1. One-way communication with supply owners		
i. Periodic campaigns on traditional and social media platforms	National, regional, and/or local	To provide continuous exposure to appropriate information and promote awareness
ii. Periodic mailing and/or e-mailing to SPS owners	National, regional, and/or local	To provide continuous exposure to appropriate information and promote awareness
2. Two-way information exchange with supply owners		
iii. Workshops aimed at supply owners	Local	To promote behavioural change
iv. Stands at relevant regional and community-based events aimed at the general public	Local	To promote behavioural change
v. School events	Local	To promote future custodianship
vi. Citizen science initiatives	National, regional and/or local	To promote awareness, and subsequent behavioural change
vii. Periodic surveys and/or focus groups	National, regional and/or local	To continuously evaluate long-term communication campaigns, measure their progress, and provide information to improve subsequent engagement mechanisms

3. Further support of supply owners		
vii. Points of contact (e.g. helpline, local advisers)	National and/or regional	To provide continuous support following behaviour uptake
4. Coordination with other relevant stakeholders		
viii. Periodic mailing and/or emailing to relevant organisations [a] and service providers [d]	National, regional, and local	To provide continuous exposure to appropriate information and promote cooperation between different stakeholders
viii. Workshops and training events aimed at relevant organisations [a]	National, regional, and local	To promote cooperation between different stakeholders
ix. Workshops and training events aimed at relevant service providers [d]	National, regional, and local	To promote cooperation between different stakeholders. Participation in these can be rewarded certificates and inclusion in registered list (i.e. tool ii)

Supply owners = may include Small Private Supplies and household well owners; a relevant organisations = Local Authorities, relevant governmental branches, NGOs, etc.; b social media = Facebook, Twitter, and Instagram platforms, etc.; c traditional media = television, radio and newspapers; d relevant service providers = well drillers, water treatment providers, well water testing facilities, etc.

The dissemination tools in **Table 10** may also be incorporated within the three-stage learning framework adapted from Simpson and Hodgins (2002) in the promotion of well stewardship amongst rural well owners. These were originally conceptualised for community-based communications but could be adapted as part of wider communication strategies:

1) **Initial awareness stage:** The targeted audience's attention must be drawn towards the issue of groundwater contamination and the potential health risks associated with it. This can be done through a series of short and frequent messages. Traditional and social media messages may be used for this at the national, regional, and community levels.
2) **Transitional stage from awareness to behaviour change:** During this stage, the targeted audience should be actively provided with practical examples of how to protect their groundwater supplies via traditional and social media (at all levels) and interpersonal means at the community level.
3) **Behaviour change empowerment stage:** In this final stage the targeted audience moves from needing information about the need and means for groundwater protection to actively seeking information and involvement in groundwater protection efforts. To assist with this stage practical information must be widely and easily available in webpages, social media, etc. Information may also be made available through support channels (e.g. local advisors, hotlines, etc.).

The above stages may be viewed as a general framework which can be utilised as part of a cohesive communication plan. The consultation of communication professionals is once again advised in the development of such plans, as there are many complexities associated with effective behavioural change which non-experts may not be equipped to overcome. For example, as outlined previously, messages which may cause the target audience to feel threatened, must be coupled with appropriate information which elucidates how individuals can protect themselves (Witte and Allen, 2000). Moreover, as SPS and household well owners may come from distinct backgrounds and day-to-day realities, 'one-size-fits-all' approaches are very challenging (Morris et al., 2016).

Partnerships between different governmental and non-governmental organizations, service providers and public partners are also advised, to encourage consistent messaging across multiple communication channels and generate support systems which facilitate two-way communication, where possible, between disseminators and the targeted audience (Tavares and Santos, 2014; Mooney et al., 2020). Certain organisational barriers may be present, however, which further complicate the development of successful communication efforts, these are described below:

Insufficient organisational knowledge: Mooney et al., (2020) highlights that current staff (e.g. awareness officers and health inspectors) at LAs are often ill-equipped to develop engagement strategies due to lack of expertise or limited time in light of other contractual commitments. Moreover, there is a noted deficit of communication and educational expertise at the government level (Mooney et al., 2020). Staff turnover is also a challenge, and over-reliance on a small number of 'experts' in the design and planning of communication campaigns may prevent their long-term implementation and success (Mooney et al., 2020).

Lack of coordination between different stakeholders: Multiple stakeholders have a role in the dissemination of well stewardship behaviours from public and private organizations to service providers (Morris et al., 201; Mooney et al., 2020), and lack of communication between these can lead to conflicting information. In Ireland, as water policy responsibilities are decentralised and departmental funding and staffing is constantly rearranged (de Loë and Kreutzwiser, 2005; Mooney et al., 2020) there may be risks of discrepancies between communication efforts in different counties. Moreover, noted lack of communication and consultation with non-state actors, such as well drilling companies, laboratories, NGOs, treatment providers, etc., impedes the development of tailored communication messages and engagement with supply owners at the community level (Mooney et al., 2020).

Limited policy and monetary resources: Adequate funding and policy support are required for the development and implementation of successful long-term communication campaigns. However, findings from Mooney et al. (2020) stress that policymakers still need to be persuaded of the benefits of information dissemination activities. This is highlighted by the limited direction provided to LAs in the design of private water supply engagement activities and materials under the 'National Inspection Plan' (EPA 2017c; Mooney et al., 2020). Lack of longstanding departmental structures and monetary funding is a common hinderance to long-term dissemination strategies, and subsequent failure to achieve desirable behaviour changes (Mooney et al., 2020). In the absence of appropriate policy, communication practitioners are forced to avail of alternative policy agendas and pre-existing social capital to promote risk information to private supply owners (de Loë and Kreutzwiser, 2005; Mooney et al., 2020).

6.3. Beyond communication

As outlined in Section 6.1, there are multiple cognitive and practical barriers which can prevent the uptake of desired behaviours (Morris et al., 2016; Mooney et al., 2020), and overcoming all of them through communication efforts alone may be very challenging. Where this is the case, other tools have been outlined in the literature which may be used to further motivate well stewardship:

Active enforcement of guidelines: The enforcement of regulations regarding SPSs are currently of responsibility of LAs, however this has been insufficient to prevent instances of non-compliance and lack of monitoring in recent years (EPA, 2015; 2017b; 2020b; 2021) likely due to limited monetary and personnel-related resources (Mooney et al., 2020). The EPA currently recommends that in case of non-compliance, SPS are audited by the suitable LA, and tailored recommendations provided (EPA, 2015). This tool is indeed a crucial component of well stewardship enforcement, where available, and should by employed more consistently. For this, however, resource availability and governance structures currently in place for this purpose much be re-evaluated.

Interactive mapping tool: this has been recommended by MacDonald Gibson et al. (2017) to identify whether a supply is at risk of contamination. The use of this tool could motivate individuals to take ownership of their own supply maintenance. Such application has already been developed by the Irish EPA, the "Private Well Assessment App" (available at http://erc.epa.ie/water/wells/#.YAqx5uj7RPY), however it is notably undersubscribed. The EPA tool would greatly benefit from a more attractive and user-friendly interface and content upgrades in line with added evidence-based recommendations, as well as active dissemination as part of communication campaigns.

Generation of multi-channel support systems: Continuous support in addition to information dissemination is crucial to address complacency and promote behavioural change among targeted individuals (Kreutzwiser et al. 2011). This may be achieved with the help of trained service providers which are most accessible to supply owners at the local (community) level, such as farming advisers, well drillers, treatment providers, local groups, etc. or via direct points of contact (phone or email) available at the national/regional levels, similar to the system put in place by Gas Networks Ireland, for example. The latter approach would indeed be highly recommended, as current decentralization of water policy regulators (de Loë and Kreutzwiser, 2005; Mooney et al., 2020) causes supply owners that seek assistance to be bounced back between different governmental organisations. Support avenues at the national/regional level may also be beneficial particularly in response to extreme weather events, which can significantly affect a supply's watery quality and are predicted to occur more frequently in the next few years due to climate change (Pall et al., 2011; Arnell and Gosling, 2016).

Further monetary assistance: Financial constrains remain one of the largest barriers to well stewardship behaviour uptake (see Section 6.1). To overcome this, the expansion and further development of financial aid programmes is strongly recommended. Source improvement and treatment grants, for example, which are currently available only to household wells, could be extended to SPSs. Moreover, as regular well testing is considered a precursor to most desirable well stewardship practices, grants made available for this purpose are also advised, particularly in areas of known contaminant hotspots (e.g. arsenic). Regarding this barrier a recent US-based study also recommends the "development of affordable private-well contract maintenance services, in which private-system users pay subscription fees for routine well maintenance and testing, and for assistance in installing and maintaining water-treatment systems where contamination is identified. These services could also include septic system maintenance in areas where septic systems threaten private-well water quality" (MacDonald Gibson et al., 2017).

6.4. Summary of communication recommendations

Multiple measures which are crucial for the successful communication and promotion of well stewardship practices among SPSs have been recommended in Sections 6.1 and 6.2 of this document and are summarised in **Table 9** and **Table 10**. Moreover, in section 6.3 it is highlighted that further support and enforcement may be necessary. However, the implementation of these measures may not be possible under current organisational structures and resource allocation systems.

As outlined in Section 6.2, there are many organisational barriers which prevent the development and implementation of a successful well stewardship promotion, such as current lack of longstanding departmental structures and monetary funding (Mooney et al., 2020). For that reason, a governance organisation focused solely on SPSs is once again recommended, with a similar structure to that employed by the NFGWS. Moreover, relevant custodians at the community level, such as the Teagasc Agricultural Sustainability Support and Advisory Programme (ASSAP), may be given a greater role in communicating the importance of source protection through the implementation of existing regulations. Based on the findings from this section the responsibilities of a new organisation would include (1) producing and disseminating communication materials; (2) carrying out audits/inspections of SPSs with compliance issues; (3) supporting, training, and coordinating relationships between relevant stakeholders; (4) offering official training and registration of SPSs service providers; and (5) providing continuous support to private supply owners via helplines or other assistance systems at the local level (e.g. local advisors from ASSAP).

7. Conclusion and final recommendations

This report provides in-depth analyses of the contaminants which most commonly affect private groundwater sources used for drinking in Ireland, encompassing Small Private Suppliers (SPSs) and private household wells. The *key contaminants* identified in Irish groundwaters were faecal coliforms (including *E. coli*), arsenic, and nitrate, found in exceedance of permissible values in 69.6, 4.2 and 4.0% of EPA groundwater monitoring stations at least once from 2014 to 2019, respectively. The same three contaminants were also the most frequently exceeded in registered SPSs across the country from 2014 to 2019, as reported by LAs, causing non-compliance in up to 6.8 (*E. coli*), 3.5 (arsenic), and 2.9% (nitrate) of SPSs annually. These results show that action is required to improve the drinking water quality provided by these sources in Ireland.

Principal source protection and management practices recommended for the prevention/management of contamination (with emphasis on *key contaminants*) are provided in this report (see

Table 7 and **Table 8**, respectively). It is not sufficient, however, to produce best-practice evidence-based guidance if this information is not appropriately and actively communicated to supply owners and custodians themselves. Accordingly, specific communication material messages and dissemination tools were also suggested (**Table 9** and **Table 10**, respectively) which may be used as part of cohesive communication campaigns.

The successful implementation of all evidence-based recommendations outlined in this report, however, require significant changes in the current SPS supervisory structures. Thus, we recommend the formation of a novel national organisation, similar in structure to the NFGWS, to manage specific SPS-related issues. The responsibilities of this new organisation, based on issues identified in the current study, should include the nine principal recommendations listed below:

1) **Register all Small Private Supplies in the country**
2) **Produce hotspot maps for naturally occurring groundwater contaminants (e.g. arsenic) and enforce/promote assistance of a qualified hydrogeologist during the drilling of new supplies in high-risk areas**.
3) **Enforce source protection, and relevant agricultural and domestic wastewater treatment regulations**, including minimum setback distances to drinking water supplies, with changes (where applicable) to the Good Agricultural Practices for the Protection of Waters and Code of Practice for Wastewater Treatment Systems for Single Houses.
4) **Update/create regulatory and communication documents in line with evidence-based recommendations, which**:
    - Clearly outline the risks of contamination to groundwater supplies and consumers,
    - Provide step-by-step evidence-based guidance regarding supply protection/ management (including well construction and maintenance, water test interpretation, treatment options, etc.), and
    - List registered service providers.
5) **Organise periodic well stewardship dissemination campaigns at national, regional and local levels** using traditional and social media; mailing and/or emailing; workshops; stands at relevant events (e.g. ploughing championship); school events; and/or citizen science initiatives (this may be particularly effective with regards to the water testing behaviour). Campaigns should also be periodically (annually/biannually) evaluated, not only to measure progress but also to improve subsequent messages, and dissemination/engagement mechanisms.

6) **Ensure that all Small Private Supplies with compliance issues are audited/inspected.** During these visits, contamination risks should be identified and tailored recommendations regarding source protection and treatment, where needed, should be provided.
7) **Support, train, and coordinate relationships between relevant stakeholders at national, regional and local levels**, ranging from public and private organizations to service providers.
8) **Provide official training and registration of service providers** (e.g. well drillers, water testing facilities, treatment installation companies etc), with registration upon successful completion of training. Lists of registered providers can then be made available to Small Private Supply owners.
9) **Provide continuous support to Small Private Supply owners** via helplines or other assistance systems at the local level (e.g. local advisors).

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Appendix 1. Database searches for identification of issues associated with the occurrence of *key contaminants*

Contaminant of concern	Type of study sought	Web of Science Search	Search results	Full texts examined	Included studies
Escherichia coli and other microorganisms of faecal origin	Reviews (2000-present)	TITLE: ((“Escherichia coli” OR “E coli” OR “faecal coliform” OR “fecal coliform” OR faecal OR fecal OR pathogen OR microbe OR microbial) AND (“water well” OR well OR groundwater OR borehole OR drinking OR consumption OR domestic OR supply OR supplier OR household))	86*	7	7
	Irish-based studies (any-present)	TITLE: ((“Escherichia coli” OR “E coli” OR “faecal coliform” OR faecal OR pathogen OR microbe OR microbial OR microbiological OR contamination) AND (“water well” OR well OR groundwater OR borehole OR drinking OR consumption OR domestic OR supply OR supplier OR household)) AND TOPIC: (Ireland OR Irish)	22	7	7
Nitrate	Reviews (2000-present)	TITLE: ((nitrate) AND (“water well” OR well OR groundwater OR “ground water” OR borehole OR drinking OR consumption OR domestic OR supply OR supplier OR household))	38*	8	5
	Irish-based studies (any-present)	TITLE: ((nitrate) AND (“water well” OR well OR “ground water” OR groundwater OR borehole OR drinking OR consumption OR domestic OR supply OR supplier OR household)) AND TOPIC: (Ireland OR Irish)	16	6	4
Arsenic	Reviews (2000-present)	TITLE: ((arsenic) AND (“water well” OR well OR groundwater OR “ground water” OR borehole OR drinking OR consumption OR domestic OR supply OR supplier OR household) AND (reduction OR mitigation OR protection OR management OR treatment))	14*	7	6
	Irish-based studies (any-present)	TITLE: ((arsenic) AND (“water well” OR well OR groundwater OR “ground water” OR borehole OR drinking OR consumption OR domestic OR supply OR supplier OR household)) AND TOPIC: (Ireland OR Irish)	6	3	3

* Number only represents studies classified as “reviews” among all database search results

Appendix 2. Database searches for identification of effective communication strategies

Type of study sought	Web of Science Search	Search results	Full texts examined	Included studies
Reviews (2000-present)	TITLE: ("private water" OR "private well" OR "well owner" OR "private supplier" OR "well water" OR "private groundwater" OR "private ground water" OR "drinking groundwater" OR " drinking ground water" OR "drinking") AND TITLE: (translat* OR communicat* OR intervention OR knowledge OR awareness OR dissemination OR mitigat* OR promot* OR strateg* OR perception OR outreach OR guid*)	70*	6	5
Irish-based studies (any-present)	TITLE: ("private water" OR "private well" OR "well owner" OR "private supplier" or "well water" OR "private groundwater" OR "private ground water" OR "drinking groundwater" OR " drinking ground water" OR "drinking") AND TITLE: (translat* OR communicat* OR intervention OR knowledge OR awareness OR dissemination OR mitigat* OR promot* OR strateg* OR perception OR outreach OR guid*) AND TOPIC: (Ireland OR Irish)	19	3	2

* Number only represents studies classified as "reviews" among all database search results