The James Hutton Institute

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Effect of maintenance and different raw water quality parameters on ultraviolet (UV) disinfection in private water supplies in Scotland

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Glossary

Biodosimetry – a method for determining UV dose by challenging a UV unit, under controlled conditions, with micro-organisms for which the UV sensitivity (the relationship between UV dose and extent of inactivation) is known. The UV dose achieved by the unit is then inferred from the observed inactivation of the challenge micro-organisms. Biodosimetry is currently the only accepted method for the independent validation of UV units.

Colour - In this report, colour refers to 'true' colour, where the sample is filtered through a 0.45 μm filter paper to remove turbidity. Turbidity increases the colour.

Log removal – the extent of removal (or for UV, inactivation) of micro-organisms by treatment, expressed logarithmically. Log removal relates to per cent removal as follows:

1 log removal = 90% removal
2 log removal = 99% removal
3 log removal = 99.9% removal
4 log removal = 99.99% removal

LP UV – Low Pressure UV. A type of UV lamp which contains a small amount of mercury, emits UV light at essentially one wavelength (254 nm), operates at a temperature of 30-50 ^{o}C, and has a relatively low energy consumption. This is currently the most appropriate type of UV lamp for small-scale use.

MP UV – Medium Pressure UV. A type of UV lamp which contains a relatively large amount of mercury, emits UV light across a spectrum of wavelengths, operates at a temperature of 600-900 ^{o}C, and has a relatively high energy consumption. MP lamps use energy less efficiently than LP lamps, but have a much greater UV output for a given size of lamp. MP UV is generally only considered for large-scale (municipal) use.

UV – Ultraviolet irradiation. That part of the electromagnetic spectrum within the wavelength range 100-400 nm. The UVC range (200-280 nm) is effective for inactivating micro-organisms, by disrupting DNA (or RNA). DNA absorbs UV strongly at 254 nm, which corresponds to the output wavelength of LP UV lamps.

UV_{254} abs – Ultraviolet absorbance, a quantitative measure of the attenuation of UV light intensity as it passes through water. Specifically, refers to the absorbance of UV light with a wavelength of 254 nm by 1 cm of water. Expressed in units of cm^{-1}. Related to UVT by the formula,

$$UVT = 100 \times 10^{-UV_{254}abs}$$

Hence 0 cm^{-1} UV_{254} abs = 100% UVT.

UV Dose – product of UV intensity (usually mW cm^{-2}) and contact time (seconds) to provide a dose in mJ cm^{-2}. Dose is usually specified at a wavelength of 254 nm. It cannot be measured directly.

UV Intensity – the total radiant power of light converging on a point on a surface, per unit area of that point (usually mW cm^{-2}).

UVT – Ultraviolet transmittance, a quantitative measure of the attenuation of UV light intensity as it passes through water. Specifically, the per cent transmittance of UV light with a wavelength of 254 nm through 1 cm of water. 100% UVT means there is no attenuation of intensity; 0% UVT means no UV light penetrates more than 1 cm. Expressed as %. Related to UV_{254} abs by the formula,

$$UV_{254}abs = -\log_{10}\left(\frac{UVT}{100}\right)$$

Validation – confirmation by an independent certifying body that a UV unit will achieve some specified dose under defined operating conditions (flow rate, UVT). The only validation method currently accepted by regulatory bodies is biodosimetry.

Executive summary

The Executive Summary provides an overview of the aims, objectives, and main conclusions arising from this work. For a more detailed synopsis of the technical aspects of this work, see Technical summary.

Aims and objectives of this work

Local Authority Environmental Health Officers (EHOs) and The Drinking Water Quality Regulator (DWQR) for Scotland are concerned at the lack of improvement in bacteriological compliance of private water supplies (PWS) in Scotland, particularly 'Type A' supplies (those serving more than 50 individuals or supplying a volume that exceeds 10 m^3 per day or, regardless of size, supplying a commercial operation - holiday accommodation or food production premises). Many of these private supplies utilise ultraviolet (UV) disinfection.

The Scottish Government has funded research to gain a better understanding of the factors preventing improvement in bacteriological compliance, specifically in relation to water treatment systems which include UV disinfection. The James Hutton Institute and WRc have collaborated to produce this report aimed at satisfying the following objectives:

i. To identify the extent and impact of poor installation, operation and maintenance of water treatment systems.

ii. To monitor and assess the effectiveness of a statistically significant range of private water supplies to determine the impact of raw water quality, particularly colour and total organic carbon, on the effectiveness of UV disinfection.

iii. To review existing information available on the impact of water quality, particularly colour and total organic carbon at levels commonly found in Scottish raw waters, on UV disinfection systems.

iv. To provide guidance and information for Local Authorities and the owners and users of private water supplies on the impact of raw water quality on UV disinfection and the importance of maintenance

These 4 objectives were tackled through:

1. A literature review of Existing Information on Impact of water quality on UV performance (Section 2)
2. A monitoring campaign of 34 private water supplies to link system maintenance and raw water quality to tap water quality (Section 3)
3. A laboratory experiment to understand ability of UV to deactivate *E. coli* across a range of Scottish water typologies (Section 4)

Main Findings/Conclusions:

Water is generally suitable for disinfection by UV (40 mJ cm^{-2}) if:

- UV transmittance (UVT) of the water to be disinfected is >75 %
- The colour of the water to be disinfected is 20 °H or lower as colour reduces UVT
- The turbidity of the water should be < 4 NTU as turbidity reduces UVT
- The concentration of iron in the water is < 50 μg l^{-1} (to minimise lamp fouling)
- The concentration of manganese is <20 μg l^{-1} (to minimise lamp fouling)
- Hardness is <120 mg l^{-1} $CaCO_3$ (unlikely to be an issue in Scotland)
- Pre-filters and water softeners should be designed to achieve the above levels at all times even taking seasonal differences into account (where practicable, during the design phase, water samples should be taken quarterly)
- Water storage (tanks, etc.) should be prior to UV treatment to prevent post-treatment re-activation

Removal of colour pre-UV treatment:

High levels of colour in source waters are fairly commonplace in Scotland. It is important to reduce colour as it impairs UVT. There are two main filter substrates that can be used:

- Carbon is effective but how effective depends on the nature of the high colour i.e. percentage of solids that will be contributing to the colour level so it's important to remove as much turbidity as possible before the colour removal (absorption process) takes place. Depending on the level of colour, high capital costs can be incurred in replacing the spent media. However, the main advantage of this type of treatment is there is no waste stream produced by the treatment itself and the spent media is classified as inert and so can be disposed of to landfill.
- Organic Scavengers (ion exchange process) are effective at reducing the colour level, but in some cases the organic material in coloured water supplies can foul the surface of the media causing a breakdown in the treatment with the only options being to acid wash the media surfaces "as often as required" or replace the media if the media has been installed for a reasonable time period (>1 year). There is a waste stream produced by this treatment process that uses concentrated Brine to regenerate the media much like a Softener does and it is not always possible to mix this with another waste stream to dilute the concentration further beyond the dilution that takes place during the regeneration. In such a case, it is not possible from an environmental perspective to discharge the waste stream to a ground soak away and there is the issue of where the waste can be discharged.

Where colour levels are 20 - 40 °H either forms of the above treatment have been used successfully. Above this, small-scale field trials are needed to establish if the treatment is going to work sufficiently. Where levels are much higher e.g. in a very "changeable" surface water supply i.e. river intake then the colour level can be 100 + °H where any form of recognised treatment will not reduce the colour level to the maximum guide limit.

Main Conclusions from literature review of Existing Information on Impact of water quality on UV performance (Section 2):

With regard to water quality:

1. Knowing the minimum UV transmittance (UVT) of a water source is essential for UV disinfection applications to ensure the target dose can be applied.
2. The relationship between colour and UVT is not absolute, but 20 °H likely represents the maximum colour for practical application of UV disinfection.
3. The limited literature available suggests that 4 NTU would not be expected to compromise UV disinfection performance.

With regard to reactivation:

1. From the available information, reactivation is unlikely to be an issue provided a sufficient UV dose for disinfection is applied.

With regard to current standards:

1. Of the current standards relating to validation of UV units for disinfection, the NSF/ANSI 55 – 2012 standard (Class A) is, in principle, the most relevant for the small-scale units likely to be installed for the primary disinfection of private supplies. This standard requires validation by biodosimetry of a UV dose of 40 mJ cm^{-2}.

With regard to UV units currently installed, or available for, private water supplies:

1. Small UV units suitable for single-household use are unlikely to have validation to a recognised standard.
2. Such UV units are often rated for a dose of 30 mJ cm^{-2}. Although this dose is referred to in sales literature variously as a ‘standard’ or ‘protocol’, the basis for so doing is not clear. There is no apparent justification for recommending a rated dose of less than that required for public water supply applications, 40 mJ cm^{-2}.

Main Conclusions from Research Monitoring Campaign (Section 3):

1. Quarterly sampling should be sufficient to gain a reasonable appraisal of water quality at a given site for the purposes of determining whether treatment systems are adequate

2. Bacterial failure of tap water is most strongly correlated with source water TOC; i.e. high TOC source waters are more likely to result in bacterial fail at the tap

3. TOC is highly related to colour and turbidity; all of which affect UV transmittance

4. Bacterial failure of tap water is more likely to occur if levels of TOC in source waters increase, e.g. during/after heavy rain events

5. Source waters located in catchments dominated by extensive or intensive livestock grazing seem to be more vulnerable to compromised tap water quality

6. In agreement with 3 and 4 above, source waters located in catchments dominated by extensive or intensive livestock grazing are more likely to have elevated levels of TOC

7. Water supply types that have greater connectivity to the surface environment (surface supplies, shallow wells) are more vulnerable to fluctuations in TOC, and hence bacterial fail at the tap

8. Where treatment systems are well maintained (filters and UV bulb), risk of bacterial failure of the tap water is much reduced. Well maintained treatment systems show considerable robustness to fluctuations in source water bacterial loads

Main Conclusions from Laboratory Experiment (Section 4):

1. Domestic-scale UV systems (40 mJ cm^{-2}) if properly maintained should be effective at deactivating *E. coli* in a range of post-filtered waters typical of those found in PWS in Scotland. New UV units should remain effective even if water quality parameters deteriorate (e.g. during heavy rain events) but this ability is likely to decrease over time due to e.g. lamp fouling.

In the **Technical Summary**, guidance notes are provided for anyone who is currently operating a UV disinfection system for a private water supply, or for anyone thinking of installing one. The guidance notes cover the following:

What is UV disinfection?
Is water quality important?
What dose is needed?
Is operation straightforward?
What maintenance is required?
As well as the benefits and disbenefits of using UV disinfection as opposed to other treatment systems.

Recommendations for future work

1. Gaining a better understanding the relationship between colour and UVT, and approaches for reducing colour in water pre-UV treatment is of key importance to improving tap water quality from PWS.

2. The data and information presented here could be used to develop a decision support system for treatment system design based on information relating to catchment typology, outcome of the current risk assessment, as well as water quality parameters.

3. The monitoring work described in this report could be further focussed to investigate more intensive sampling at a small number of selected sites, e.g. those that have shown chemical concentrations in the tap water as being elevated compared to the source water in order to understand better the effects that specific treatment systems can have on tap water quality if those systems are not properly maintained.

4. A number of the conclusions (in particular Sections 3 & 4) suggest that effective system maintenance is a key aspect of maintaining water quality. Further social research with volunteers to investigate barriers to effective maintenance, limitations in skills/knowledge, and therefore incentives that would encourage PWS owners to take a more active role in system maintenance could be conducted.

5. Re-visit and potentially re-design the PWS risk assessment.

6. Detailed laboratory investigation into UV bulb-fouling potential of different water typologies and how UVT is affected over time. This experiment would provide water type-specific recommendations on bulb maintenance and replacement.

Technical summary & Guidance notes

This section provides a synopsis of the technical sections (focusses on Sections 2 - 4) of this report, as well as associated guidance. This section provides a text-only summary with references made to more detailed information in the main report.

Section 1 – Introduction

Aims:

i. Why has the microbiological quality of private water supplies not improved, despite considerable upgrades to many supplies?

ii. How effective is UV as a disinfectant in private water supplies under different environmental and water quality conditions?

iii. What maintenance of private water supplies is being carried out, and what knowledge do the owners and users of private water supplies have of the need for adequate installation, operation and maintenance of their supply systems?

Objectives:

i. To identify the extent and impact of poor installation, operation and maintenance of water treatment systems.

ii. To monitor and assess the effectiveness of a range of private water supplies to determine the impact of raw water quality, particularly colour and total organic carbon, on the effectiveness of UV disinfection.

iii. To review existing information available on the impact of water quality, particularly colour and total organic carbon at levels commonly found in Scottish raw waters, on UV disinfection systems.

iv. To provide guidance and information for Local Authorities and the owners and users of private water supplies on the impact of raw water quality on UV disinfection and the importance of maintenance.

Approach:
The above objectives were addressed through the following specific activities:

a) Characterisation and monitoring of the effectiveness of UV disinfection on 34Type B supplies with existing UV treatment during different weather conditions and water quality conditions across different geographical areas of Scotland (Section 3).
b) Monthly monitoring of a subset of six of the above sites which appear to be proficiently installed operated and maintained to evaluate how UV disinfection is affected by differing water quality conditions (Section 3).
c) Review of existing information available on the impact of water quality on UV disinfection systems, including information on available technology for the removal of colour and other organics and its effectiveness under different water quality conditions (Section 2).
d) Survey of supplies to evaluate i) prevalence of correct installation, operation and maintenance carried out on UV systems ii) owner/user level of understanding of importance of maintenance of supplies.

Section 2 - Review of Existing Information on Impact of water quality on UV performance

Main water quality factors impacting on UV performance:
UV light is an effective approach to deactivation of microorganisms in water (Table 2.4; Table 2.5) However, there are three water quality-related issues impacting UV performance: UV transmittance/absorbance (Section 2.1), which determines the rate of attenuation of UV light; particulates (Section 2.1.2), which, aside from contributing to attenuation (loss of intensity of the UV radiation), may shield organisms from exposure to the UV; and fouling of the lamp by colloidal particles (Section 2.1.3), which will reduce lamp output over time.

The intensity of UV light passing through water is attenuated by the presence of UV-sorbing substances present in the water, thus there is a relationship between transmittance and absorbance (Section 2.1; Figure 2.1). The extent of attenuation is termed UV transmittance (UVT) and is defined as 'the percent transmittance in the medium when the path length is 1 cm and the wavelength is 254 nm' (Bolton, 2008). The majority (if not all) domestic-scale UV lamps for water treatment are tested for efficacy in waters with high UV transmittance (usually >90% UV transmittance). Raw waters used for PWS often have UVT <90%, thus the potential efficacy of UV water treatment is likely to be compromised. Substances present in raw waters that can decrease UVT include natural organics, phenolic compounds, some metals and anions such as iron and manganese (see Table 2.2). These substances can increase the colour (measured in degrees Hazen, °H) of raw water, thus there is also a relationship between colour and UVT (Table 2.1) that suggests UV treatment is significantly compromised where colour exceeds 20 °H.

Particulates (Section 2.1.2) can affect the performance of UV reactors by sheltering pathogens from UV radiation and scattering UV light. Scottish drinking water quality regulations (SSI, 2006) impose for Type A supplies, a maximum turbidity of 4 Nephelometric Turbidity Units (NTU) with the stated requirement that 'every effort should be made to achieve 1 NTU whenever possible'; and for Type B supplies, a maximum turbidity of 4 NTU. The limited literature outlined above suggests that 4 NTU would not be expected to compromise disinfection performance.

Compounds present in the water can foul the external surfaces of the lamp sleeves and other wetted components of UV reactors (Section 2.1.3). Fouling on the surface of lamp sleeves will reduce the applied UV intensity and consequently disinfection efficiency. Waters containing high concentrations of iron (> 100 $\mu g\ l^{-1}$), hardness (> 140 mg l^{-1} $CaCO_3$), hydrogen sulphide and organics are more susceptible to fouling (USEPA, 2006), and effective cleaning regimes are needed. Lamp cleaning can be by chemical (citric and phosphoric acids are sometimes used, or proprietary solutions) or mechanical means, or some combination of the two. Automated cleaning is unlikely in domestic-scale systems, the onus will be on the owner to comply with the method and frequency stipulated by the supplier. Lamp cleaning is relatively straightforward for domestic units and should be possible for anyone with basic DIY skills although the quartz sleeve is breakable and requires delicate handling.

A further complication is the fact that a number of microorganisms including *E. coli* and *Cryptosporidium parvum* have been shown to display a degree of reactivation following treatment with UV (~0.7 % reactivation per day of dark storage) (Section 2.2). This basically means that the microorganisms are able to re-grow post disinfection. This has been shown to occur in both dark (e.g. storage tanks) and light conditions. The best way to mitigate against this is to ensure that UV treatment occurs as close to the tap as practicable and that no water is stored post irradiation with UV. When UV is installed in a domestic or private supply, residence time between UV and tap will likely be very short when the tap is open, but very long overnight or during periods when the occupants are absent therefore it might be sensible for residents to run their tap for a short while first thing in the morning and when they return after periods of absence.

Standards and guidelines applicable to UV disinfection systems:
Standards and guidelines applicable to potable water UV disinfection systems have been published by (and are summarized in Table 2.3 with further detail in Appendix 7.1.1):

- National Sanitation Foundation/American National Standards Institute (NSF/ANSI)
- British Standards Institute (BSi)
- US EPA
- Austrian Standards Institute (ÖNORM)

- DVGW Germany
- National Water Research Institute/Water Research Foundation (NWRI/WRF)

Of the current standards relating to validation of UV units for disinfection, the NSF/ANSI 55 – 2012 standard (Class A) is, in principle, the most relevant for the small-scale units likely to be installed for the primary disinfection of private supplies. The common objective is to provide independent confirmation that a UV reactor achieves some specified level of performance within the range of operating conditions defined by the supplier. All require dose validation by biodosimetry, the principles of which are outlined in Section 2.3.2. A synopsis of some suppliers of UV treatment systems in Scotland is provided in Section **Error! Reference source not found.**.

Section 2 - Main conclusions:
With regard to water quality:

1. Knowing the minimum UV transmittance (UVT) of a water source is essential for UV disinfection applications to ensure the target dose can be applied. As UVT is affected by weather conditions, preferable to measure this during the autumn to obtain a representative minimum.
2. The relationship between colour and UVT is not absolute, but 20 ^{o}H likely represents the maximum colour for practical application of UV disinfection.
3. The limited literature available suggests that 4 NTU would not be expected to compromise UV disinfection performance; regardless, it is still desirable to keep NTU to a minimum and would recommend pre-filtering prior to UV disinfection.

With regard to reactivation:

1. From the available information, reactivation is unlikely to be an issue provided a sufficient UV dose for disinfection is applied.

With regard to current standards:

1. Of the current standards relating to validation of UV units for disinfection, the NSF/ANSI 55 – 2012 standard (Class A) is, in principle, the most relevant for the small-scale units likely to be installed for the primary disinfection of private supplies. This standard requires validation by biodosimetry of a UV dose of 40 mJ cm^{-2}.

With regard to UV units currently installed, or available for, private water supplies:

1. Small UV units suitable for single-household use are unlikely to have validation to a recognised standard.
2. Such UV units are often rated for a dose of 30 mJ cm^{-2}. Although this dose is referred to in sales literature variously as a ‘standard’ or ‘protocol’, the basis for so doing is not clear. There is no apparent justification for recommending a rated dose of less than that required for public water supply applications, 40 mJ cm^{-2}.

Section 3 – Research Monitoring of PWS

In order to investigate factors that affect the efficacy of UV treatment systems, 34 private water supplies (PWS) across Scotland were selected for in-depth study (Figure 3.1). A detailed description of the site selection methodology can be found in Section 3.2. Each of the PWS included in this study was investigated over a period of 12 months (December 2013 – November 2014) using a holistic approach that included basic quarterly monitoring of water quality parameters (both source and supply; Section 3.3.3), catchment-level risk assessment of potential threats to water quality (Section 3.3.2), sampling and analysis of soil of direct influence on source water quality (Section 3.3.4); as well an in-depth researcher-led questionnaire aimed at understanding the PWS owner/users understanding, use and maintenance of their system. A full description of the questionnaire development can be found in Section 3.3.1, and the questionnaire itself is provided in Appendix 7.2. A sub-set of 6 PWS that appeared to be well maintained were also sampled on a monthly basis in order to understand more about variability in water quality (both source and supply) throughout the year.

All water samples (source and supply) were analysed within 6 hours of collection with the exception of a small number of sites where logistics/owner availability dictated otherwise. In those cases, samples were analysed within 12 hours. All standard water analyses were undertaken by Scottish Water laboratories which are accredited to the UKAS standard “Drinking Water Testing Specification Accreditation Requirements for Sampling and Testing in Accordance with the Drinking Water Testing Specification (DWTS)” (Section 3.3.3). Water analyses undertaken covered the main microbiological and chemical water quality parameters, including UV transmittance and parameters known to affect UV transmittance (Table 3.1).

Results and implications

A detailed description of all results is available in Section 3.4.

Characterisation of pass vs. fail PWS

A combined analysis of the tap water quality (pass vs. fail) alongside the questionnaire responses identified that while there was significant variability between the different PWS included in this study, sites where potable water consistently met quality criteria and UV disinfection appeared to be effective where consistency of maintenance approach and source water quality are achieved:

- Installations were generally carried out by professionals
- Filtration of some sort – coarse, fine or both is installed prior to UV disinfection
- Filters are maintained and bulbs are replaced at least annually
- Owners tend to be involved in maintenance
- Dominance of arable/garden (non-grazing/upland) catchments
- Generally low numbers of coliforms in soil adjacent to PWS source.
- Source waters are low pH (acidic), generally low in colour, turbidity, TOC and often low in metals.
- UV transmittance of source water is usually high.

Conversely, Sites failing microbiological parameters can be broadly characterised as having much more variable/inconsistent maintenance and operation, as well as more variable source water quality (while good maintenance cannot guarantee overcoming the challenges of a poor quality water supply, it does give the PWS owner the best chance at improving water quality):

- Installations carried out by either professionals, plumbers or owners
- Filtration of some sort – coarse, fine or both is installed prior to UV disinfection
- Filters are maintained and bulbs are replaced at least annually for most sites
- Maintenance may be carried out by owners or professionals
- Dominance of grazing/upland catchments
- Range of soil loading of coliforms
- Soils tend to be high in OM
- Sources waters are tend to be high in metals, TOC and colour
- UV transmittance may be low, high or variable.
- Potable water tends to fail once or more for high concentrations of metals and colour.

- Microbiological fails do not necessarily correspond directly with chemistry fails
- Indication that past water quality events are important – spikes of poor source water quality may influence subsequent potable water chemical and microbiological quality potentially through leaching from saturated filters or fouling of UV lamp surfaces.

Combined data analysis

Detailed analyses (including in-depth statistical analyses) of the combined water quality (quarterly; monthly), risk assessment scores, soils and questionnaire data (see Figure 3.2-Figure 3.46) revealed a number of trends from which the following inferences can be made, albeit cautiously given the limited statistical power of the dataset. These inferences form the main conclusions (Section 5) of this study:

1. quarterly sampling should be sufficient to gain a reasonable appraisal of water quality at a given site for the purposes of determining whether treatment systems are adequate

2. Bacterial failure of tap water is most strongly correlated with source water TOC; i.e. high TOC source waters are more likely to result in bacterial fail at the tap

3. TOC is highly related to colour and turbidity; all of which affect UV transmittance

4. Bacterial failure of tap water is more likely to occur if levels of TOC in source waters increase, e.g. during/after heavy rain events

5. Source waters located in catchments dominated by extensive or intensive livestock grazing seem to be more vulnerable to compromised tap water quality

6. In agreement with 3 and 4 above, source waters located in catchments dominated by extensive or intensive livestock grazing are more likely to have elevated levels of TOC

7. Water supply types that have greater connectivity to the surface environment (surface supplies, shallow wells) are more vulnerable to fluctuations in TOC, and hence bacterial fail at the tap

8. Where treatment systems are well maintained (filters and UV bulb), risk of bacterial failure of the tap water is much reduced. Well maintained treatment systems show considerable robustness to fluctuations in source water bacterial loads

Section 4 – Laboratory study on UV effectiveness

Due to the various practical constraints on the design of the PWS monitoring programme (as discussed in Section 3.2) it was not possible to sample from and monitor PWS representative of the entire range of source water typologies used as PWS in Scotland. Also, as with any field study, it was impossible to control for a myriad of different factors that may contribute to water quality. Due to these two reasons, it was decided to conduct a laboratory trial to investigate the efficacy of UV for deactivation of *E. coli* across a selection of possible water typologies not covered as part of the PWS monitoring programme. The main hypotheses of this experiment were:

1. Die-off will increase with increasing levels of UV irradiance.

2. Water typology will impact on levels of die-off. Specifically waters with greater turbidity levels will provide enhanced protection against UV radiation and favour survival.

The aims of this experiment were to:

1. Investigate the efficacy of UV light to deactivate *E. coli* in a range of water typologies including the effect of turbidity (NTU), water pH, trace element concentrations, and other factors.

2. Plot dosimetry curves (see Section 2.3.2) for each water typology by measuring *E. coli* deactivation over a range of different UV doses.

3. Extrapolate these laboratory results to the main PWS monitoring dataset, i.e. the dosimetry curves provide the relationships between various water quality parameters and UV efficacy. These relationships can then be applied to the main monitoring data in order to make inferences about the effectiveness of UV treatment across all monitored PWS within this project.

While it was not possible to determine full dosimetry curves from this experiment, full details are provided (Section 4) for completeness. A single conclusion that domestic-scale UV systems (40 mJ cm^{-2}), if well maintained, are effective at deactivating *E. coli* in a range of post-filtered waters typical of those found in PWS in Scotland. New bulbs should remain effective even if irradiation drops as low as 10 mJ cm^{-2}, however this ability will decrease over time due to e.g. lamp fouling. Further work is needed to investigate how UV effectiveness declines with fouling for different water typologies.

Overall conclusions

1. Quarterly sampling should be sufficient to gain a reasonable appraisal of water quality at a given site for the purposes of determining whether treatment systems are adequate

2. Domestic-scale UV systems (30 – 40 mJ cm^{-2}) are effective at deactivating *E. coli* in a range of waters typical of those found in Scotland. They should remain effective even if irradiation drops as low as 10 mJ cm^{-2}

3. Bacterial failure of tap water is most strongly correlated with source water TOC; i.e. high TOC source waters are more likely to result in bacterial fail at the tap

4. TOC is highly related to colour and turbidity; all of which affect UV transmittance

5. Bacterial failure of tap water is more likely to occur if levels of TOC in source waters increase, e.g. during/after heavy rain events

6. Source waters located in catchments dominated by extensive or intensive livestock grazing seem to be more vulnerable to compromised tap water quality

7. In agreement with 3 and 4 above, source waters located in catchments dominated by extensive or intensive livestock grazing are more likely to have elevated levels of TOC

8. Water supply types that have greater connectivity to the surface environment (surface supplies, shallow wells) are more vulnerable to fluctuations in TOC, and hence bacterial fail at the tap

9. Where treatment systems are well maintained (filters and UV bulb), risk of bacterial failure of the tap water is much reduced. Well maintained treatment systems show considerable robustness to fluctuations in source water bacterial loads

Guidance notes

These notes provide guidance for those considering the installation of UV disinfection for a private supply. They are arranged as a series of questions, for which one or two answers are given. Where two answers are given, the first is intended to raise the important issues

in a non-technical manner, while the second answer provides a more technical response to the question.

The guidance notes relate strictly to UV disinfection and provide no information on alternatives.

Guidance on ultraviolet (UV) disinfection for private supplies

Private water supplies in Scotland must comply with the applicable statutory regulations, currently (2014) The Private Water Supplies (Scotland) Regulations 2006, which set out the water quality standards that must be met and the obligations of the person(s) responsible for a private supply.

The person(s) responsible for a private supply should not install UV disinfection without taking advice (e.g. from a treatment installation company) as to the suitability of UV generally, the possible requirement for pre-treatment, and the selection of an appropriate UV unit.

What is UV disinfection?

UV disinfection is the inactivation of micro-organisms by exposure to UV light. This exposure causes structural damage which prevents the micro-organisms from causing infection.

The extent of the exposure, and thus damage caused, depends on the intensity of the UV light reaching the micro-organisms, and the time of the exposure. It is expressed in terms of UV dose.

UV light with wavelengths in the range 200-300 nm is absorbed by the DNA and RNA of micro-organisms, causing structural damage at the molecular level which prevents cells from replicating. If cells cannot replicate, the micro-organisms cannot cause infection.

The extent of the structural damage is in proportion to the amount of UV light absorbed. Therefore, micro-organisms must be exposed to sufficient UV light to ensure adequate disinfection. The extent of the exposure depends on the intensity of the UV light reaching the micro-organisms, and the time of exposure. It is expressed in terms of UV dose.

Is water quality important?

Yes. UV disinfection should never be installed without first determining that the water quality is suitable, for two reasons.

First, the efficacy of UV disinfection is dependent on the intensity of UV light to which the micro-organisms are exposed. The UV light must pass through water to reach the micro-organisms. There are many substances that may be dissolved in water which absorb UV light, notably natural organic matter and especially organic matter which gives colour to water. The more UV light absorbed by such substances, the lower the intensity reaching the micro-organisms. Also, particles in the water may shield micro-organisms from, and depending on their nature also absorb, UV light. A minimum requirement, therefore, for a potential UV disinfection installation, is that the water be clear and not cloudy (free of turbidity) and of low colour.

The second consideration is that some dissolved substances – for example organic matter, iron, manganese and hardness – may deposit over time on the sleeve which separates the UV lamp from the water, a process known as fouling. Fouling reduces the intensity of UV light entering the water.

As an indication of the water quality required for UV disinfection, the water should at least meet the statutory physical and chemical standards for Type A supplies as set out in The Private Water Supplies (Scotland) Regulations 2006. Local Authorities can take water samples and provide advice.

If current water quality is unsuitable for UV disinfection, it may be possible to pre-treat the water to an acceptable quality. Water treatment equipment is available to remove turbidity, colour, iron and manganese, and hardness, and suppliers of UV units may be able to provide an appropriate combination of treatment equipment as a complete package. Grants, which are not means tested, of up to £800 are available from local authorities, who should be consulted before any work is started.

The primary water quality parameter of relevance is Ultraviolet Transmittance (UVT), which is the per cent transmittance of UV light with a wavelength of 254 nm through 1 cm of water. The higher the UVT, the lower the attenuation, or reduction, of UV intensity as it passes through the water; and thus the greater the UV intensity to which micro-organisms are exposed. *As a guideline*, UVT should be greater than 75 % for UV disinfection to be practicable. UVT is not a regulated water quality parameter, but colour, which strongly influences UVT, is regulated for Type A supplies (maximum 20 mg l^{-1} Pt/Co). The UVT of water of colour greater than 20 mg l^{-1} Pt/Co will probably be too low for UV disinfection to be practicable.

Turbidity is regulated for Type A supplies (maximum 4 NTU, with the requirement to achieve 1 NTU “whenever possible”) and Type B supplies (maximum 4 NTU). The majority

of suppliers recommend the installation of a 5 μm filter prior to the UV unit, which should ensure that this is achieved.

Dissolved iron may contribute to lower UVT and/or to fouling. Iron is regulated for Type A supplies (maximum 200 μg Fe l^{-1}) but not Type B supplies, but should be determined for any supply for which UV is proposed. *As a guideline*, the iron concentration should be less than 200 μg Fe l^{-1} for UV disinfection to be practicable.

Dissolved manganese may contribute to fouling. Manganese is regulated for Type A supplies (maximum 50 μg Mn l^{-1}) but not Type B supplies, but should be determined for any supply for which UV is proposed. *As a guideline*, the manganese concentration should be less than 50 μg Mn l^{-1} for UV disinfection to be practicable.

Hardness is not regulated for drinking water supplies, but may contribute to fouling. Water in Scotland is generally soft, but some sources, particularly boreholes, may be relatively hard. If there's any doubt, hardness should be determined for a supply for which UV is proposed. *As a guideline*, the hardness should be less than 120 mg $CaCO_3$ l^{-1} for UV disinfection to be practicable.

What dose is needed?

To be consistent with international standards that apply to UV disinfection for public water supplies, it is recommended that UV units installed for the disinfection of private water supplies should be rated for a UV dose of 40 mJ cm^{-2}.

UV light is hazardous and can cause serious burns – never expose eyes or skin to UV light

UV dose cannot be measured directly. The dose applied in a given UV unit depends on the intensity of light emitted by the UV lamp, the geometry of the unit, the flow rate of the water, and the quality of the water. A given UV unit will generally have a notional rating in terms of maximum flow rate at which a specified dose is achieved for a specified water quality, but suppliers should also have available performance curves which relate flow rate to water quality for given dose(s).

Some suppliers of small-scale UV units rate them for a dose of 30 mJ cm^{-2}, while others rate them for 40 mJ cm^{-2}. These ratings are indicative, with a unit typically being described in terms of the flow rate at which the rated dose will be applied given some specified water quality. This means that in practice, if the unit is operated at a lower flow rate but with the

specified water quality, the dose will be higher; or if operated at the specified flow rate but with lower quality water, the dose will be lower.

For private supplies there is currently no regulatory requirement for UV units to have third-party certification. Some available units are, however, certified to an American standard (NSF/ANSI 55) for point-of-use and point-of-entry UV units, which also stipulates a dose of 40 mJ cm^{-2} for primary disinfection.

There are some NSF/ANSI 55-certified UV units rated for 16 mJ cm^{-2}. These are only suitable for supplementary disinfection of mains water, and must not be used for primary disinfection.

Is operation straightforward?

On a day-to-day basis UV units require little attention to operate them. They should be left switched on. Operation must always be in accordance with the supplier's instructions.

The simplest UV units have only a visual power on/off indicator, so there is little to be monitored. Additional instrumentation that may be available as optional extras, or built-in to more expensive units, includes a run-time indicator, a UV intensity meter, and audible/visual warnings linked to these. These will indicate when maintenance is required.

Frequent switching on/off shortens the life of a UV lamp, and should be avoided. Also, a UV lamp takes a few minutes to reach maximum output when switched on, and adequate disinfection is not assured during this warm-up period.

The intensity of a UV lamp declines over time, in much the same way as a household fluorescent lamp. Suppliers factor in this decline in intensity when rating the performance of UV units and will specify a maximum run-time for a lamp, which is when it must be replaced. This normally approximates to a year when a lamp operates continuously, and so for UV units without a run-time indicator, annual replacement is usually specified. In a premises which is not occupied year-round (e.g. holiday let), having a run-time indicator enables lamp replacement on the basis of actual run-time. Deterioration in lamp output caused by frequent switching on/off will not be apparent from run-time monitoring alone. A UV intensity meter allows the decline in intensity resulting from fouling or lamp ageing to be monitored, informing the user when maintenance is required.

Two further options that may be available, more likely for UV units designed for larger flow rates, are a UVT monitor and a temperature sensor. A UVT monitor provides assurance that water quality is within that for which the unit has been specified, and warning if it isn't. UV units designed for larger flow rates may be fitted with 'high output' lamps which operate

at a higher temperature than standard lamps. During periods of no flow the water retained in the body of a 'high output' UV unit may become hot. Linking a temperature sensor to a dump valve enables the unit to be automatically flushed through with cold water at some pre-set temperature.

What maintenance is required?

UV units require little maintenance. However, depending on water quality, it may be necessary to disassemble the unit periodically to clean away fouling. If a UV intensity meter is fitted, the sensor will also require periodic cleaning. Many Local Authorities provide private water supply maintenance plans – an example from Highland Council may be found at
http://www.highland.gov.uk/download/downloads/id/485/private_water_supply_-_water_safety_maintenance_plan

Because of lamp ageing the UV lamp must be replaced at some specified interval or run-time. This is typically annually.

Additional maintenance will be required for any pre-treatment installed (e.g. periodic replacement of cartridge filters).

All maintenance must be carried out as per manufacturer's recommendations.

What are the advantages and disadvantages of UV disinfection?

Advantages

Effective against a wide range of infectious micro-organisms, including viruses, bacteria and protozoa (e.g. *Cryptosporidium*).

Does not add chemicals to the water.

Does not impart any taste on the water.

Compact.

Straightforward to operate.

Only basic maintenance is required.

Disadvantages

Does not provide any long lasting disinfection effect. Water treated by UV should not be stored prior to consumption. The water should be treated as close to the point of use as practicable.

It is not possible to monitor UV dose. To be sure that the target dose is achieved, the UV unit must be operated in accordance with the specifications (minimum water quality, maximum flow rate) and instructions provided by the supplier, including any maintenance (e.g. cleaning; lamp replacement).

Loss of power will mean loss of disinfection, so a reliable electricity connection is important.

Main Report

1. Introduction

1.1. Background to project

Scotland possesses nearly 189,000 private drinking water supplies that serve approximately 3.5 % of the population (DWQR 2014). Further individuals may encounter private water supplies when they stay in accommodation during holidays or visiting family and friends. This group are likely to be more vulnerable to adverse health effects since they may not have acquired immunity.

Supplies vary in size from those that serve one household to those that serve hundreds of people. The owner or person who uses the supply is responsible for its maintenance. The sources of private water supplies also vary, including surface water such as streams and rivers as well as private impoundment reservoirs, and groundwater such as wells and boreholes or springs where groundwater issues naturally at the surface from an aquifer.

The quality of drinking water provided by private water supplies is variable. Some supplies have adequate treatment and are well managed, but others undoubtedly present a risk to health where treatment is not sufficiently robust with respect to the quality of the source water or operation and maintenance is inadequate.

In 2006, the Private Water Supplies (Scotland) Regulations were introduced that required appropriate treatment systems to be installed on all PWS. In the case of Type B supplies, this was a stipulation when properties were sold and grant schemes were (and are) available to PWS owners to help with costs of system upgrade. Local Authorities have put considerable time and effort into improving and upgrading treatment systems of PWS and improvement has been seen for individual supplies, and more general improvement in a number of water quality parameters.

Bacteriological compliance has not significantly improved since the regulations were introduced, even after improvements have been made to private water supplies. The reasons for this are not clear, although there is a suspicion that various factors may be contributory, including the effectiveness of ultraviolet disinfection to cope with the range of water quality encountered in Scotland, and awareness by owners and supplies of the requirement for adequate treatment that is properly installed, operated and maintained.

Local Authority EHOs raised a number of concerns over bacterial compliance of PWS with Scottish Government/DWQR. In response, The Scottish Government invited proposals to gain a better understanding of the factors preventing improvement in bacteriological compliance. The James Hutton Institute and WRc have collaborated to produce this report aimed at satisfying the objectives specified in the invitation to tender, which were:

v. To identify the extent and impact of poor installation, operation and maintenance of water treatment systems.

vi. To monitor and assess the effectiveness of a statistically significant range of private water supplies to determine the impact of raw water quality, particularly colour and total organic carbon, on the effectiveness of UV disinfection.

vii. To review existing information available on the impact of water quality, particularly colour and total organic carbon at levels commonly found in Scottish raw waters, on UV disinfection systems.

viii. To provide guidance and information for Local Authorities and the owners and users of private water supplies on the impact of raw water quality on UV disinfection and the importance of maintenance

1.2. Background and policy context

Private water supplies are regulated by the Private Water Supplies (Scotland) Regulations 2006 which transpose the revised European Drinking Water Directive (Council Directive 98/83/EC), and update earlier Regulations. Regulation is overseen by local authorities.

Regulatory guidance requires owners of PWS to use risk assessments from 'source to tap' to implement an effective drinking water surveillance programme. A distinction is drawn between a “Type A” supply serving more than 50 individuals, a volume that exceeds 10 m^3 d^{-1} or, regardless of size, a commercial operation (holiday accommodation or food production premises), and a “Type B” supply that represents all other supplies. The drinking water quality for Type A supplies is governed by the European Drinking Water Directive, whereas standards for Type B supplies are specified in the PWS regulations.

Local authorities have a duty to complete Risk Assessments on all Type A supplies. These involve assessing the source of the supply and the surrounding water catchment area to identify potential sources of contamination, and also checking on storage tanks, treatment processes and pipework. Local authorities must also carry out the appropriate water quality sampling and analysis as specified in the Regulations. They have the power to take

appropriate steps to ensure that water quality meets the standards required by the Regulations. There is no requirement for local authorities to routinely test Type B supplies.

The latest report (2014) from the Drinking Water Quality Regulator (DWQR) for Scotland has revealed that bacteriological indicators comprised the greatest proportion of all non-compliances on PWS. Compliance to the coliform standard was lowest, with 29.3 % of Type A and 41.6 % of Type B supplies failing to meet this. Coliforms are not necessarily a public health risk but serve to demonstrate that the integrity of the water supply has been compromised and may permit ingress of faecal pathogens. Of continuing concern for the DWQR was the proportion of non-compliance to the *E. coli* standard. In 2011, 15.1 % of Type A supplies and 22.2 % of Type B supplies were non-compliant. There had been a steady increase in compliance for Type B supplies, but the situation has not improved for Type A supplies between 2010 and 2011 and has remained exactly the same at 84.9 %.

UV irradiation has been used for many years for disinfection of drinking water. UV systems for drinking water applications usually use Low Pressure (LP), Low Pressure High Output (LPHO) or Medium Pressure (MP) mercury vapour lamps.

UV output from LP and LPHO UV lamps is nearly all at 254 nm, providing greater disinfection efficiency than MP UV lamps, which emit a much wider range of wavelengths. However, MP UV lamps have a higher power output (over a much wider range of wavelength), and units are therefore much smaller than LP units. LPHO or MP lamps are usually provided in larger systems.

UV dose (sometimes referred to as fluence) is the product of the UV intensity (mW cm^{-2}, sometimes referred to as fluence rate) and the exposure time (seconds), and is usually expressed in units of mJ cm^{-2} (equivalent to mWs cm^{-2}). In more sophisticated treatment systems (e.g. associated with public supplies or some of the larger type A private supplies), control systems maintain the target dose during variation in flow rate and water quality (UV transmittance), and also make allowance for deterioration of the lamp output over time. In most Type B supplies, the effective UV dose is rarely monitored and as lamps degrade over time or are affected by water quality/maintenance issues, the UV dose reaching the water may be considerably diminished without the knowledge of the supply owner/user. Therefore regular maintenance is required.

A key element of UV regulatory guidance for public water supply in Europe and the USA is the requirement to provide validation of the applied dose using challenge micro-organisms (biodosimetry). This is needed to allow for hydraulics of UV reactors, in which different flow paths through the reactor result in different applied doses. Biodosimetry establishes the effective dose based on the degree of inactivation of the challenge micro-organism, which can then be used to predict the degree of inactivation of defined pathogens such as *Cryptosporidium*.

Originally, UV was not believed to be effective for *Cryptosporidium*. However, in the late 1990s, implementation of alternative measurement techniques for *Cryptosporidium* inactivation indicated that it was highly effective at conventional disinfection dose levels.

There are no dose validation requirements for the smaller UV units used for disinfection of private water supplies, but equipment suppliers would be expected to ensure that the doses used provide effective disinfection.

Substances present in the water, such as natural organics, phenolic compounds, suspended solids (often measured as turbidity), metals (iron) and anions (nitrates, sulphites) can absorb UV, reducing the effective dose. Controls on larger systems can allow for this to some extent, and UV reactors are usually sized to deliver the required UV dose under specified minimum UV transmittance conditions for the application. Determining the quality of aquatic dissolved organic matter (DOM) can be as important as quantity in terms of interactions with UV irradiation. Particulates (turbidity) can also affect the performance of UV reactors by shielding pathogens from UV radiation and by scattering UV light. It is generally believed that turbidity above 10 NTU would be needed to have a significant impact through this mechanism, although standards in some European countries specify turbidity of less than 1 NTU for UV application.

Compounds present in the water can foul the external surfaces of the lamp sleeves and other wetted components of UV reactors. Fouling on the surface of lamp sleeves can reduce the applied UV intensity and consequently disinfection efficiency. Waters containing high concentrations of iron (more than 0.1 mg l^{-1}), hardness (greater than 140 mg l^{-1} as $CaCO_3$), hydrogen sulphide and organics are more susceptible to fouling, and effective cleaning regimes are needed, which are often automated on larger systems.

Concerns over disinfection by-products are much less for UV compared with chemical disinfectants such as chlorine. Combinations of high UV dose with MP lamps and high nitrate in the water may lead to excessive nitrite formation.

1.3. Scope of works

1.3.1. Aims

Research is required to determine the following:

iv. Why has the microbiological quality of private water supplies not improved, despite considerable upgrades to many supplies?

v. How effective is UV as a disinfectant in private water supplies under different environmental and water quality conditions?

vi. What maintenance of private water supplies is being carried out, and what knowledge do the owners and users of private water supplies have of the need for adequate installation, operation and maintenance of their supply systems?

1.3.2. Objectives

The objectives of the research are:

v. To identify the extent and impact of poor installation, operation and maintenance of water treatment systems.

vi. To monitor and assess the effectiveness of a range of private water supplies to determine the impact of raw water quality, particularly colour and total organic carbon, on the effectiveness of UV disinfection.

vii. To review existing information available on the impact of water quality, particularly colour and total organic carbon at levels commonly found in Scottish raw waters, on UV disinfection systems.

viii. To provide guidance and information for Local Authorities and the owners and users of private water supplies on the impact of raw water quality on UV disinfection and the importance of maintenance.

1.3.3. Approach

The above objectives were addressed through the following specific activities:

e) Characterisation and monitoring of the effectiveness of UV disinfection on 34Type B supplies with existing UV treatment during different weather conditions and water quality conditions across different geographical areas of Scotland.
f) Monthly monitoring of a subset of six of the above sites which appear to be proficiently installed operated and maintained to evaluate how UV disinfection is affected by differing water quality conditions.
g) Review of existing information available on the impact of water quality on UV disinfection systems, including information on available technology for the removal of colour and other organics and its effectiveness under different water quality conditions.
h) Survey of supplies to evaluate i) prevalence of correct installation, operation and maintenance carried out on UV systems ii) owner/user level of understanding of importance of maintenance of supplies.

2. Review of Existing Information on Impact of water quality on UV performance

There are three water quality-related issues impacting UV performance: UV transmittance/absorbance, which determines the rate of attenuation of UV light; particulates, which, aside from contributing to attenuation (loss of intensity of the UV radiation), may shield organisms from exposure to the UV; and fouling of the lamp by colloidal particles, which will reduce lamp output over time.

2.1. UV Transmission/absorbance

The intensity of UV light is attenuated by UV-absorbent substances as it passes through water. UV transmittance (UVT) is a quantitative measure of the extent of this attenuation, being defined as 'the percent transmittance in the medium when the path length is 1 cm and the wavelength is 254 nm' (Bolton, 2008). Knowing the minimum UVT of a water source is essential for UV disinfection applications to ensure the target dose can be applied.

UV transmittance is related to UV_{254} absorbance:

$$UVT = 100 \times 10^{-A} \qquad [2.1]$$

Where:
A = absorbance at 254 nm in 1 cm cell
UVT = transmittance, %

This relationship is shown in Figure 2.1

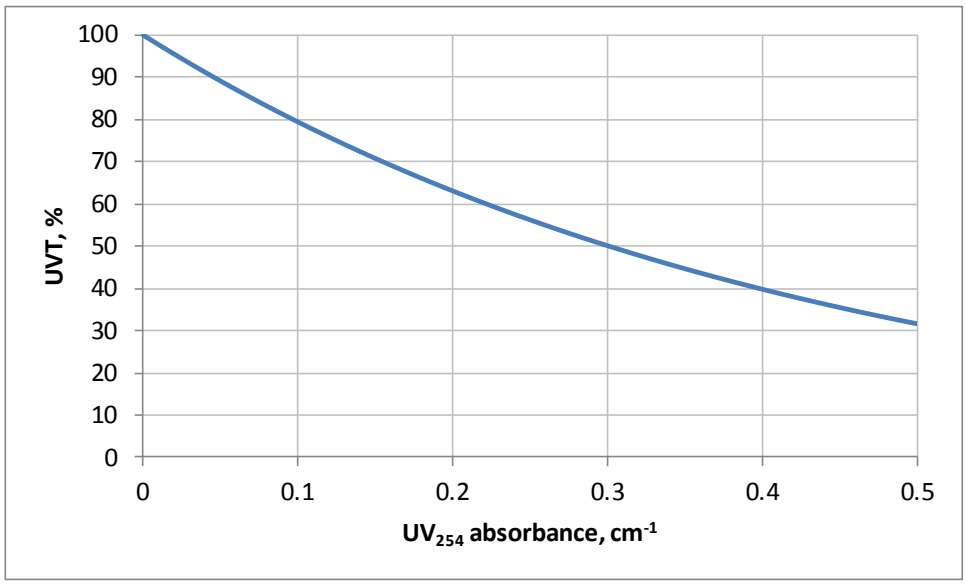

Figure 2.1- Relationship between UVT and UV_{254} absorbance

UVT can therefore be calculated from the standard laboratory measurement of UV_{254} absorbance. If absorbance is measured with a cell path length other than 1 cm, the UVT at the measurement path length is first calculated, and then converted to the corresponding value at 1 cm. Alternatively, the absorbance can be converted to absorbance at 1 cm, and UVT then calculated. Absorbance is proportional to path length, but it can be seen from the above relationship that UVT is not. To convert between UVT measured at different path lengths:

$$UVT_z = 100\left[\frac{UVT_y}{100}\right]^{z/y} \qquad [2.2]$$

Where:
UVT_z, UVT_y = UVT in path lengths z, y, %

For example:
If y = 1 cm and UVT_y = 63.1 %, then if z = 10 cm, UVT_z = 1.0 %
If y = 10 cm and UVT_y = 63.1 %, then if z = 1 cm, UVT_z = 95.5 %

If absorbance is measured with a cell path length of z cm, conversion to absorbance in a 1 cm cell is simply:

$$A = \frac{A_z}{z} \qquad [2.3]$$

Where:
A = absorbance at 254 nm in 1 cm cell
A_z = absorbance at 254 nm in z cm cell
z = cell path length, cm

Substances present in water that can decrease UVT include natural organics, phenolic compounds, some metals and anions such as iron and manganese. In coloured waters from peaty catchments the colour is a consequence of, and the measured value will correlate with, dissolved organic carbon (DOC) (e.g. Figure 2.2); and UV_{254} absorbance is also an artefact of, and will correlate with, DOC (e.g. Figure 2.3, for two Scottish sources). So although there is no universal relationship between **colour** and UV_{254} absorbance, these two determinands can be expected to correlate for a given water source, such that a higher value of either will correspond to a lower UVT.

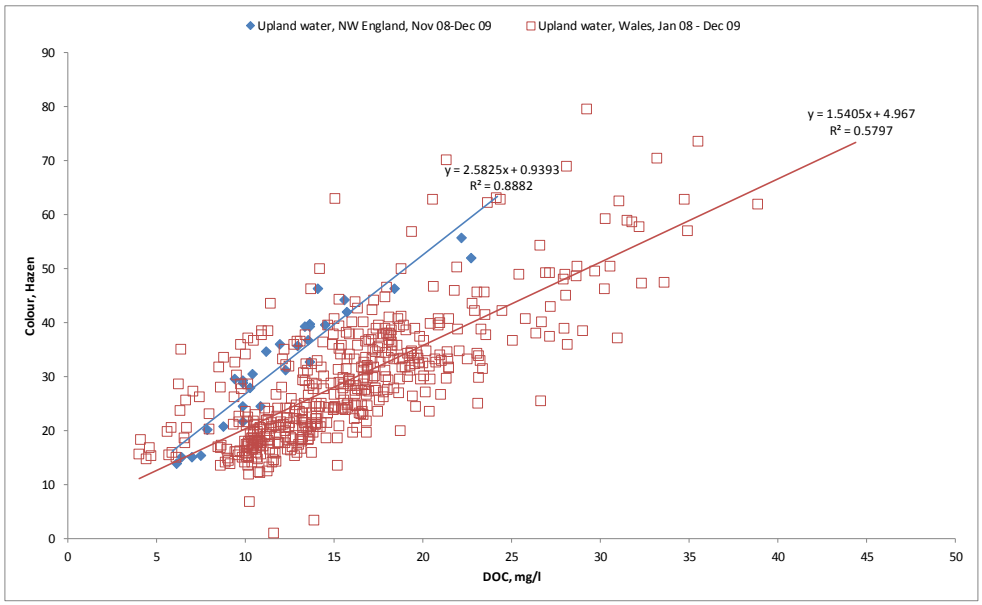

Figure 2.2 Example correlations between colour and DOC

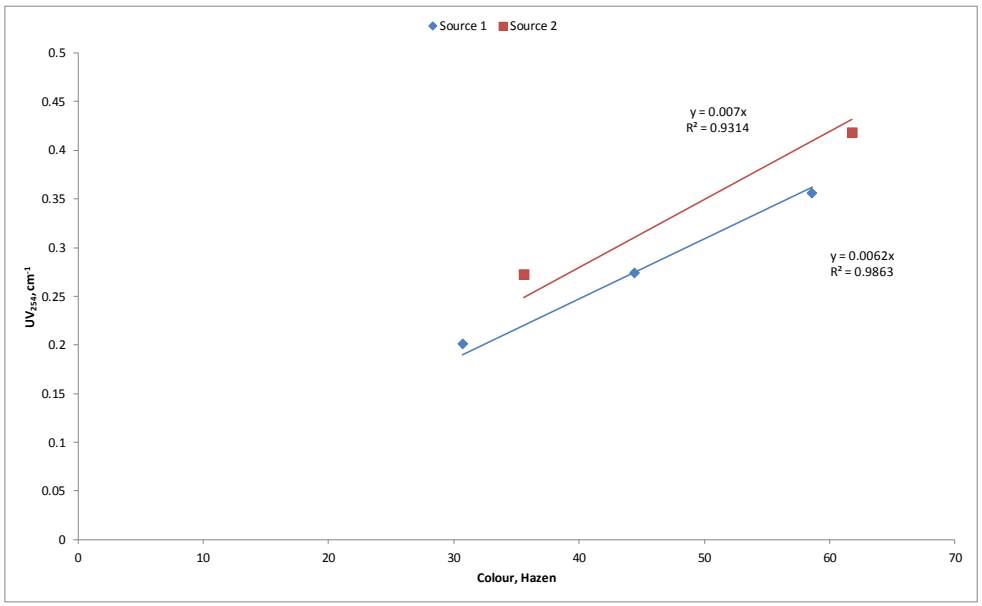

Figure 2.3 Example data describing relationships between colour and UV_{254} absorbance

Taking the average of the correlations in Figure 2.3, the impact of colour on UVT would be as indicated in Table 2.1.

Table 2.1 Example correlation between colour and UVT

Colour, Hazen (°H)	UVT, %
2.5	96.3
5	92.7
10	85.9
20	73.8
40	54.5
80	29.6

As noted above, the actual correlations between DOC, colour and UVT will vary between sources, and possibly seasonally for a given source, but Figure 2.3 and Table 2.1 serve to illustrate that appreciable colour in a water source is an indicator of low UVT, which must be factored into any UV disinfection equipment proposed for that source. As an indication of the visual impact of colour, according to Australian water quality guidelines (2013):

'A true colour of 15 ^{o}H can be detected in a glass of water, and a true colour of 5 ^{o}H can be seen in larger volumes of water, for instance in a white bath. Few people can detect a true colour level of 3 ^{o}H, and a true colour of up to 25 ^{o}H would probably be accepted by most people provided the turbidity was low.'

German regulations applying to UV disinfection give guideline values of UV_{254} absorbance ≤ 0.1 cm^{-1}, and UVT (1 cm) ≥ 70.8 % (Eggers, 2009)[1] (from Figure 2.3 this would suggest a maximum colour of the order 10 – 20 ^{o}H). Norwegian regulations require UVT (1 cm) ≥ 78.6 % (Lund, 2009). VIQUA, manufacturer of Sterilight UV units designed for residential and small-scale commercial use, recommend that UVT should be > 75 %. Under Scottish drinking water quality regulations (SSI, 2006), Type A private supplies have a maximum permissible colour of 20 ^{o}H; if the source colour is greater than this, additional treatment will be necessary to reduce it. Any such treatment should be upstream of the UV. No maximum permissible colour is specified for Type B supplies. Cross-referencing the German and Norwegian UVT guidelines with Table 2.1, it is evident that 20 ^{o}H approximates to the limit of practical application for UV disinfection.

UV absorption coefficients (a measure of how much UV light is absorbed by a specific substance – the greater the absorption, the greater the reduction disinfection potential) at 254 nm for some inorganics that might be found in water are given in Table 2.2. The 'impact threshold concentration' is the concentration that will decrease the UVT (1 cm) at 254 nm from 91 to 90%.

Table 2.2 UV absorbance characteristics of inorganic ions (Source: Bolton (2008); USEPA (2006))

	Molar absorption coefficient ($l.mol^{-1}.cm^{-1}$)	Impact threshold concentration (mg/l)
Ammonium ion (NH_4^+)	~ 0	
Calcium ion (Ca^{2+})	~ 0	
Ferric ion (Fe^{3+})	4,716	0.057
Ferrous ion (Fe^{2+})	28	9.6
Magnesium ion (Mg^{2+})	~ 0	
Manganous ion (Mn^{2+})	~ 0	
Permanganate (MnO_4^-)	657	0.91
Phosphate ion species ($H_2PO_4^-$, HPO_4^{2-})	~ 0	

[1] These values are inconsistent, since UVT (1 cm) = 70.8% corresponds to UV_{254} absorbance = 0.15 cm^{-1}.

	Molar absorption coefficient ($l.mol^{-1}.cm^{-1}$)	Impact threshold concentration (mg/l)
Sulphate ion (SO_4^{2-})	~ 0	
Sulphite ion (SO_3^{2-})	16.5	23.2

Design of UV systems needs a representative range of data for UV absorbance, taking into account seasonal influences. There are reported examples of systems being installed with insufficient data, and not being able to achieve the design dose at all times. It may be possible to use correlations with colour or TOC to fill gaps in historic data for UV absorbance.

2.1.1. Adsorption of natural organic matter

There is some evidence that natural organic matter (NOM), if present at a sufficiently high concentration, can coat the surfaces of micro-organisms and consequently reduce the sensitivity of those micro-organisms to UV. This effect was hypothesized by Templeton et al. (2006) after they had observed apparent reductions in sensitivity to UV of two viruses (T4 phage and MS2 phage) after exposure to humic acid solutions of 50 mg l^{-1} and 150 mg l^{-1} and accounting for the reductions in UVT. A similar effect was reported after a later investigation using two bacteria, *E. coli* and *Bacillus subtilis*, being statistically significant at NOM concentrations (as DOC) of 25.5 to 32.5 mg l^{-1}, depending on the source of the NOM (Cantwell et al., 2008). This represents a high DOC concentration unsuitable for Type A or B PWS, but such levels can occur in upland catchments as indicated in Figure 2.2. The combined results of Cantwell et al. (2008) and Templeton et al. (2006) at a common UV dose of 14 mJ cm^{-2} indicated that the impact of this amount of NOM was a decline in effective dose for a micro-organism of the order 15 – 20 %.

Although the shielding effect of adsorbed NOM appears real, it is unlikely to be of practical significance for potable water applications. It is evident from Figure 2.2 and Figure 2.3 that this amount of NOM will correspond to a low UVT, of the order 60 %, and, as indicated in Section 2.1, UV would be inappropriate at such low UVT. If, however, a UV system has been validated at low UVT, then it is likely that additives such as humic acid will have been used to reduce UVT as part of the test procedure, in which case shielding of the test micro-organism would have occurred and therefore been accounted for in the resultant validated dose.

2.1.2. Particulates

Particulates can affect the performance of UV reactors by sheltering pathogens from UV radiation and scattering UV light.

USEPA (2006) states that the effect of harbouring micro-organisms is not significant at turbidity of up to 10 NTU. However, one reference given for this (Passantino *et al.*, 2004) was based on a laboratory study using spiked MS2 phage, with turbidity increased by the addition of clay. This would not simulate the nature of shielding that could occur in natural waters, or in waters treated by chemical coagulation, where the micro-organisms could be embedded within the particles. Other studies have produced similar finding, but most have the same limitations. One study (Amoah *et al.*, 2005) used natural turbidity in lake water spiked with *Cryptosporidium* and *Giardia*. A reduction in *Cryptosporidium* and *Giardia* inactivation (using mouse infectivity) of up to 0.8 log and 0.4 log respectively was identified over the turbidity range 0.3 to 20 NTU, when correction was made for the UVT of the water. However, the effect was barely discernible below 10 NTU.

Scottish drinking water quality regulations (SSI, 2006) impose for Type A supplies, a maximum turbidity of 4 NTU with the stated requirement that 'every effort should be made to achieve 1 NTU whenever possible'; and for Type B supplies, a maximum turbidity of 4 NTU. The limited literature outlined above suggests that 4 NTU would not be expected to compromise disinfection performance. Nevertheless, German regulations relating to the use of UV disinfection give a guideline of ≤ 0.3 NTU (Eggers, 2009). French regulations require ≤ 0.5 NTU (Pilmis and Baig, 2009). Swiss regulations require ≤ 1.0 NTU where there is no pre-treatment, and ≤ 0.3 NTU after filtration (Bucheli, 2009). VIQUA, manufacturer of Sterilight UV units designed for residential and small-scale commercial use, recommend that turbidity be < 1 NTU. A recommendation common to the majority of suppliers of small-scale UV units is that filtration to 5 μm or better should precede the UV.

2.1.3. Compounds with fouling potential

Compounds present in the water can foul the external surfaces of the lamp sleeves and other wetted components of UV reactors. Fouling on the surface of lamp sleeves will reduce the applied UV intensity and consequently disinfection efficiency. Waters containing high concentrations of iron (> 100 μg l^{-1}), hardness (> 140 mg l^{-1} $CaCO_3$), hydrogen sulphide and organics are more susceptible to fouling (USEPA, 2006), and effective cleaning regimes are needed. German regulations give guideline values for iron (≤ 50 μg l^{-1}), manganese (≤ 20 μg l^{-1}), and 'calcite precipitation capacity' (≤ 50 mg l^{-1} $CaCO_3$) (Eggers, 2009). VIQUA, manufacturer of Sterilight UV units designed for residential and small-scale commercial use, recommend that if hardness > 120 mg l^{-1}

$CaCO_3$ the water should be softened prior to UV; and also recommend maximum concentrations for iron (300 μg l^{-1}) and manganese (50 μg l^{-1}). Regulatory limits (SSI, 2006) apply to Type A supplies for iron and manganese, of 200 μg l^{-1} and 50 μg l^{-1} respectively.

Lamp cleaning can be by chemical (citric and phosphoric acids are sometimes used, or proprietary solutions) or mechanical means, or some combination of the two. Automated cleaning is unlikely in domestic-scale systems, the onus will be on the owner to comply with the method and frequency stipulated by the supplier. Lamp cleaning is relatively straightforward for domestic units and should be possible for anyone with basic DIY skills although the quartz sleeve is breakable and requires delicate handling.

2.2. Reactivation

Some micro-organisms are able to repair the damage caused to DNA by UV disinfection. The repair mechanisms can be divided between those that occur in darkness ('dark reactivation') and those that are induced by near UV and short-wavelength visible light ('photo-reactivation') (Bolton and Cotton, 2008).

Most bacteria have been found to exhibit some degree of dark reactivation (Bolton and Cotton, 2008; Hijnen *et al.*, 2006). Some viruses can exploit the repair enzymes of the host cell to repair themselves, which possibly explains the relative insensitivity of Adenovirus to UV disinfection (Hijnen *et al.*, 2006).

Reactivation of *Cryptosporidium parvum* by both dark- and photo-reactivation has been observed, but the oocysts have lost the ability to infect host cells (Morita *et al.*, 2002); Zimmer *et al*. (2003) found no increase in infectivity in oocysts incubated for up to 5 days under dark and light conditions after exposure to LP or MP UV. Similar behaviour (i.e. reactivation without recovery of infectivity) has been reported for *Giardia lamblia* and *Giardia muris* cysts, but other studies have reported some recovery of infectivity by *Giardia* during dark-reactivation (Hijnen *et al.*, 2006); one such study reported a 3 % reactivation of *Giardia muris* cysts after 10 days in darkness after exposure to MP UV dose of 25 mJ cm^{-2}, increasing to 14 % after 20 days and 20 % after 30 days, but no reactivation after a dose of 60 mJ cm^{-2}.

USEPA (2006) states that dark-reactivation of bacteria and protozoa begins immediately after exposure to UV, so reported dose-response data account for any such reactivation; they conclude that dark-reactivation is 'not a concern' (provided, of course, that the actual UV dose at least equals that required for the target level of inactivation for the given pathogens according to the dose-response data). Hijnen *et al.* (2006) also conclude that

'dark repair does not seem very significant for the UV disinfection practice for most pathogens'.

Photo-reactivation is more prevalent than dark reactivation (Bolton and Cotton, 2008). According to Hijnen *et al.*, (2006) it requires 'prolonged exposure to (visible) light', but without quantifying 'prolonged'. Zimmer and Slawson (2002) observed photo-reactivation of *E. coli* exposed to LP doses of 5 - 10 mJ cm^{-2} to have begun after 30 minutes and reached a maximum after 3 hours – the maximum occurred sooner, the lower the dose. They observed little or no photo-reactivation when applying the same doses using MP UV.

Hijnen *et al.* (2006) note that photo-reactivation studies have typically used low UV doses and thin-film samples that provide optimal conditions for photo-reactivation, and cite other studies which have shown the extent of reactivation to decline as UV dose is increased. Their overall conclusion is that reactivation is not a significant issue for most pathogens, but they note the conflicting observations for recovery of infectivity of *Giardia* during dark-reactivation at UV doses up to 25 mJ cm^{-2}.

USEPA (2006) states that keeping UV-disinfected water in darkness for at least two hours before exposure to light prevents photo-reactivation of bacteria, and considers that such retention time will normally be provided in service reservoirs and distribution mains. They also note the general use of chemical secondary disinfection as a further barrier to reactivation of bacteria and viruses; and therefore conclude that photo-reactivation is unlikely to be an issue in municipal potable water treatment.

When UV is installed in a domestic or private supply, residence time between UV and tap will likely be very short when the tap is open, but very long overnight or during periods when the occupants are absent. Furthermore, secondary disinfection will be absent. But despite these differences in configuration (as compared with municipal treatment) it appears from the available information that reactivation is unlikely to be an issue provided a sufficiently adequate UV dose is applied.

2.3. Standards and guidelines applicable to potable water UV disinfection systems

2.3.1. Current standards

Standards and guidelines applicable to potable water UV disinfection systems have been published by:

- National Sanitation Foundation/American National Standards Institute (NSF/ANSI)
- British Standards Institute (BSi)
- US EPA
- Austrian Standards Institute (ÖNORM)
- DVGW Germany
- National Water Research Institute/Water Research Foundation (NWRI/WRF)

The documents are summarised in Table 2.3, with further details given in Appendix **Error! Reference source not found.**. The common objective is to provide independent confirmation that a UV reactor achieves some specified level of performance within the range of operating conditions defined by the supplier. All require dose validation by biodosimetry, the principles of which are outlined in section 2.3.2.

The NSF/ANSI standard appears to be the most relevant to private supplies and applies to point-of-entry and point-of-use UV equipment installed in single private residences. The standard defines two distinct classes of UV system: Class A, designed to inactivate 'bacteria, viruses, *Cryptosporidium oocysts* and *Giardia* cysts' in water that is 'not colored, cloudy, or turbid'; and Class B, 'designed for supplemental bactericidal treatment of disinfected public drinking water or other drinking water that has been (…) deemed acceptable for human consumption'. Class A systems are required to demonstrate a dose of 40 mJ cm^{-2}; Class B systems, 16 mJ cm^{-2}.
The BSi standard is the UK implementation of a European standard for LP UV devices intended for water conditioning in buildings (i.e. where the supply has already been treated); the UV device being fitted either at the point of entry of the mains supply into the building, or within the water distribution system inside the building. It further defines devices intended for disinfection ('killing or inactivating all types of pathogenic bacteria to (…) at least 99.999 % and all types of pathogenic viruses to (…) at least 99.99 %') or bactericidal treatment ('inactivating or killing bacteria present in water to an unspecified degree'). The test protocol described in this standard is adapted from the Austrian ÖNORM standard and requires validation of a 40 mJ cm^{-2} dose.

The other four standards/guidelines listed above (US EPA, ÖNORM, DVGW and NWRI/WRF) apply to municipal-scale drinking water supply applications, but are included for information purposes. US EPA have adopted the concept of log removal credits and include tables of minimum dose necessary to ensure specified log removals of regulated pathogens (primarily *Cryptosporidium* and *Giardia* – reproduced in Table 2.4); the UV system must then be validated against the target log removal. NWRI/WRF provide design guidelines for both drinking water and water reuse UV applications and describe a biodosimetry protocol suitable for meeting the US EPA requirements; they provide no advice on dose selection. The European standards, in contrast, stipulate that the UV reactor must be validated for a dose of 40 mJ cm^{-2}.

Acceptance of US EPA validation in European countries that have not developed their own standard varies. French and Swiss regulations only recognise ÖNORM or DVGW validation (Pilmis and Baig, 2009; Bucheli, 2009). Norwegian regulations accept US EPA, ÖNORM or DVGW (Lund, 2009). Dutch regulations have no specific legal requirement for validation, but require each installation to be approved by the national inspectorate; biodosimetry will almost certainly be needed as part of the approval process.

Table 2.3 Summary of standards and guidelines

Title	Reference	Dose validation test
Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule (UVDGM)	EPA 815-R-06-007 November 2006	Biodosimetry
Plants for the disinfection of water using ultraviolet radiation – Requirements and testing – Low pressure mercury lamp plants	M 5873-1 Austria ÖNORM (March 2001)	Validated dose of 40 mJ cm^{-2} at 253.7 nm. Dose validation tests using *B subtilis* spores.
Plants for the disinfection of water using ultraviolet radiation – Requirements and testing – Part 2: Medium pressure mercury lamp plants	M 5873-2 Austria ÖNORM (August 2003)	As above
UV-Geräte zur Desinfektion in der Wasserversorgung – Teil 1: Anforderungen an die Beschaffenheit, Funktion und Betrieb [UV-devices for the disinfection of the water supply – Part 1: Requirements on the design, function and action]	W 294-1 Germany DVGW / DIN (June 2006)	Not available in English. Similar to Austrian standard in terms of dose and use of *B subtilis* spores.
UV-Geräte zur Desinfektion in der Wasserversorgung; Teil 2: Prüfung von Beschaffenheit, Funktion und Desinfektionswirksamkeit [UV-devices for the disinfection of the water supply- Part 2: Tests of design, function and disinfection effectiveness]	W 294-2 Germany DVGW / DIN (June 2006)	As above
UV-Geräte zur Desinfektion in der Wasserversorgung; Teil 3: Messfenster und Sensoren zur radiometrischen. Überwachung von UV-Desinfektionsgeräten;	W 294-3 Germany DVGW / DIN	As above

Title	Reference	Dose validation test
Anforderungen, Prüfung und Kalibrierung [UV-devices for the disinfection of the water supply; Part 3: Sensors for the photometric monitoring of UV-Disinfection; tests and calibration]	(June 2006)	
Water conditioning equipment inside buildings – Devices using mercury low-pressure ultraviolet radiators – Requirements for performance, safety and testing	BS EN 14897:2006+A1:2007 European (June 2007)	Similar to Austrian standard
Ultraviolet microbiological water treatment systems	NSF/ANSI 55 - 2012 USA	Challenge test using MS2 or *Saccharomyces cerevisiae*, depending on type of device (T1 Coliphage was introduced as an alternative to *S. cerevisiae* in 2012, with the intention that *S. cerevisiae* will be removed from the standard in September 2017)
UV Disinfection Guidelines for Drinking Water and Water Reuse, 3rd Edition	NWRI/WRF 2012	Challenge test using MS2

2.3.2. Biodosimetry

Where chemical disinfection is employed it is possible to measure the residual concentration and use that, in conjunction with contact time, to judge the sufficiency of disinfection. With UV there is no measurable residual, so there is no equivalent means of assessing the efficacy of disinfection. UV intensity varies within a reactor, and micro-organisms passing through do not follow the same flow path; consequently, they do not all receive the same UV dose. To provide the necessary confidence that UV reactors are providing effective disinfection, all current standards require equipment suppliers to validate performance of their equipment by biodosimetry, and provide evidence of this validation to end users.

Biodosimetry is a validation procedure in which the UV reactor is challenged with a non-pathogenic surrogate test micro-organism under a range of operating conditions (e.g. flow rate, lamp output, UVT). There are differences between the test protocols specified in the various standards, but the principles, outlined below and illustrated in Figure 2.4, are the same:

(1) Experimental tests
   (a) The UV dose-response curve (log inactivation as a function of dose) is determined for the surrogate micro-organism using a laboratory collimated beam UV source.
   (b) The reactor is challenged with the surrogate micro-organism under a defined matrix of operating conditions, and the log inactivation determined for each set of conditions.

(2) The Reduction Equivalent Dose (RED) for each set of challenge test operating conditions is determined by comparing the log inactivation against the dose-response curve. The RED is the dose from the dose-response curve which corresponds to the log inactivation observed in the challenge test.

Under the US EPA protocol, correction factors are applied to the RED to determine the validated dose; amongst other things, these factors account for the difference in UV sensitivity between the challenge organism and the target pathogen. Under the ÖNORM/DVGW protocols, such correction factors are not required and the RED is the validated dose.

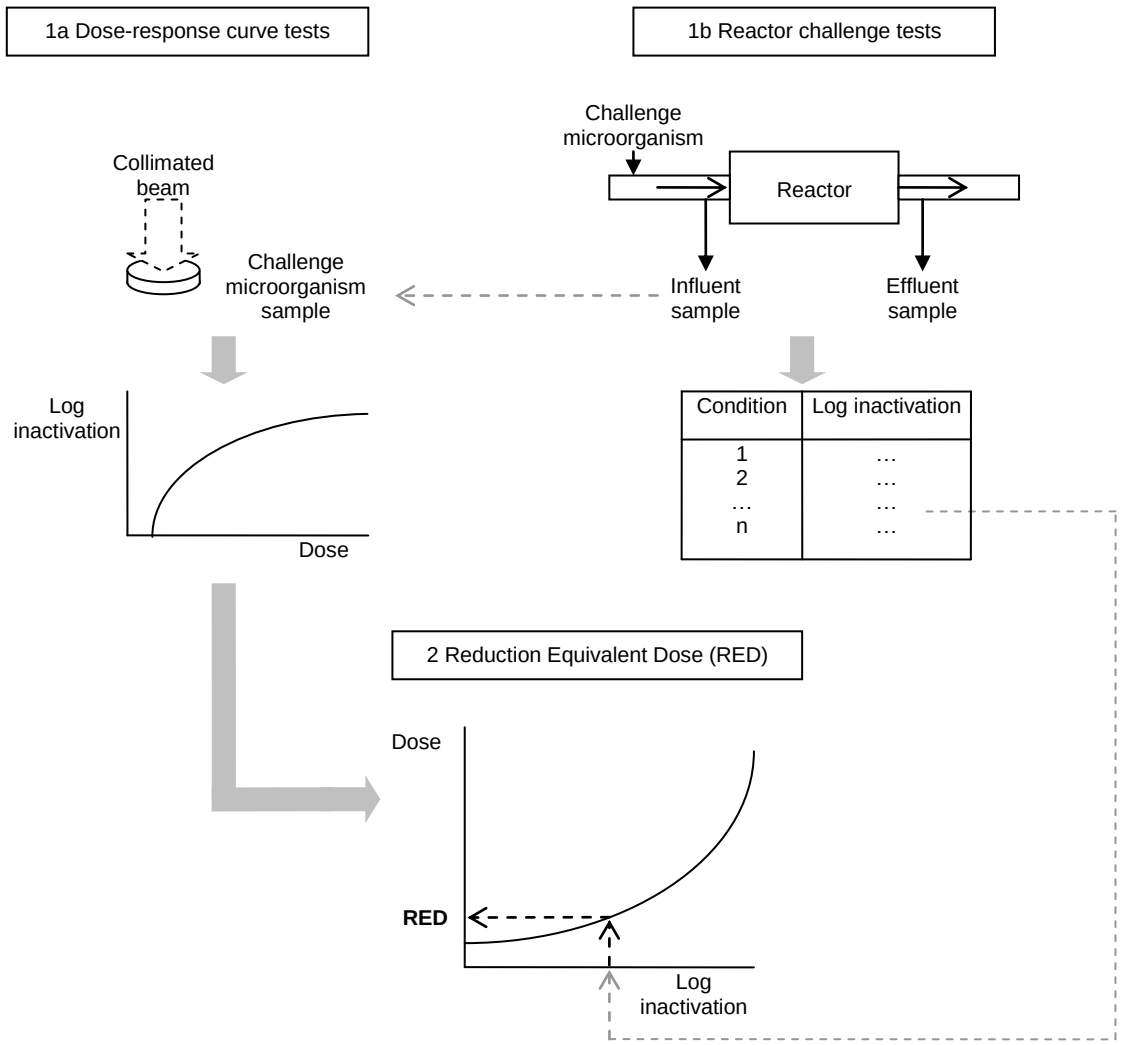

Figure 2.4 Biodosimetry validation procedure

Interpretation of dose as determined by biodosimetry is not straightforward. Strictly speaking, a dose validated by biodosimetry is meaningful only with reference to the challenge micro-organism by which it was determined. The reasons for this are as follows. The exposure to UV of each individual micro-organism passing through a reactor is different, because UV intensity within the reactor is not uniform, each micro-organism takes a different path through the reactor, and the retention time of each micro-organism is different. Consequently, there will in practice be a probability distribution of UV doses, and

the observed log inactivation will represent the overall effect of this distribution. The inactivation resulting from a given dose is determined from the dose-response curve, which is different for each type of micro-organism. Hence for a given reactor under identical operating conditions, the RED determined using one type of challenge micro-organism will not necessarily be the same as that determined using a different type.

Attempting to quantitatively compare test protocols is further complicated by differences in methodology, not least how experimental uncertainties are accounted for. One US state (CDPHE, 2013) investigated whether UV reactors validated in accordance with the NSF/ANSI Class A standard (40 mJ cm^{-2} using MS-2 Coliphage) should be permissible for small public water supplies, which would normally require equipment validated in accordance with the US EPA protocol. The conclusion was that UV reactors with 40 mJ cm^{-2} NSF/ANSI Class A validation would only be awarded treatment credits equivalent to a US EPA validated dose of 1.5 mJ cm^{-2}. In arriving at this conclusion some conservative (worst case) assumptions were made in relation to experimental uncertainties requiring quantification by US EPA but not by NSF/ANSI. The US EPA guidelines claim similar reasons for only allowing DVGW/ÖNORM-validated units a 3 log credit for *Cryptosporidium* despite the latter having been validated for a dose (40 mJ cm^{-2}) comfortably greater than the US EPA target dose for 4 log inactivation (22 mJ cm^{-2}).

2.3.3. Approved products

The regulations that apply to public water supplies for each of the countries in the UK require approval of products and substances used for water treatment and distribution (for example: Regulation 27 in Scotland; Regulation 31 in England and Wales). The list of approved products and services is common to all constituent countries. In England, the Private Water Supplies Regulations 2009 extend the requirement for Regulation 31 approval to private water supplies, but allows for inclusion in a transitional list of products/substances ‘any product or substance which has been used in no fewer than three different private supplies for at least 12 months prior to 1 January 2011’ provided there is evidence of ‘satisfactory water quality’ and ‘no history of consumer complaints or adverse health effects’. The current transitional list (version 1.6, 21/08/13) includes ranges of UV units from four suppliers. The Private Water Supplies (Scotland) Regulations 2006 do not currently extend the requirement for Regulation 27 approval to private water supplies, although there is an expectation that only approved materials are used; this will become a regulatory requirement following the forthcoming revision of the PWS legislation.

2.4. Inactivation

Examples of inactivation by UV, for a range of micro-organisms, are given in Table 2.4 and Table 2.5.

Table 2.4 UV dose (mJ cm^{-2}) for inactivation of protozoa and viruses.

Target	Log_{10} Inactivation							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Protozoa								
Giardia cysts[1]	1.5	2.1	3.0	5.2	7.7	11	15	22
Cryptosproridium cysts[1]	1.6	2.5	3.9	5.8	8.5	12	15	22
Viruses								
'Viruses'[1]	39	58	79	100	121	143	163	186
Adenovirus type 40[2]		56		111		167		
Poliovirus[2]		7		15		22		30
Adenovirus type 41[3]								112
Hepatitis A[3]								21
Coxsackie virus B5[3]								36
Poliovirus type 1[3]								27
Rotavirus SA11[3]								36
Murine norovirus[4]		7.3		14.6		21.9		29.2
Feline calicivirus[4]		6.3		12.5		18.8		25
Echovirus 12[4]		7.4		14.8		22.2		29.6

[1]USEPA (2006)
[2]Hijnen WAM, Beerendonk EF and Medema GJ. (2006)
[3]Bolton JR and Cotton CA. (2008)
[4]Park GW, Linden KG and Sobsey MD. (2011)

Table 2.5 UV dose (mJ cm^{-2}) for inactivation of spores and bacteria

Target	Log_{10} inactivation							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Spores								
B. subtilus spores[1]		28		39		50		62
B. subtilus spores[2]		56		111		167		222
Bacteria								
Campylobacter jejuni[3]								4.6
Campylobacter jejuni[2]		3		7		10		14
Clostridium perfringens[3]								23.5
Clostridium perfringens[2]		45		95		145		
Enterobacter cloacae[3]								10 (33)
Enterocolitica faecium[3]								17 (20)
E. coli[1]		3		4.8		6.7		8.4
E. coli O157:H7[3]								6 (25)
E. coli O157[2]		5		9		14		19
E. coli wild type[3]								8.1
E. coli wild type[4]								6 - 8.5
E. coli wild type[2]		5		9		14		19
Klebsiella pneumoniae[3]								20 (31)
Legionella pneumophila[3]								9.4
Legionella pneumophila[2]		3 - 8		6 - 15		8 - 23		11 - 30
Mycobacterium smegmatis[3]								20 (27)
Pseudomonas aeruginosa[3]								11 (19)
Salmonella typhi[3]								8.2
Salmonella typhi[2]		6		12		17		51
Shigella dysenteriae ATTC29027[3]								3

Shigella dysenteriae[2]		3		5		8		11
Shigella sonnei[2]		6		13		19		26
Streptococcus faecalis[3]								11.2
Streptococcus faecalis[2]		9		16		23		30
Vibrio cholerae[3]								2.9 (21)
Vibrio cholerae[2]		2		4		7		9

[1]USEPA (2010)
[2]Hijnen WAM, Beerendonk EF and Medema GJ. (2006)
[3]Bolton JR and Cotton CA. (2008) - values in brackets include photoreactivation data
[4]Bucheli-Witschel, Bassin C and Egli T. (2010)

The inactivation values for bacteria proposed by Hijnen et al (2006) are higher than those reported from by other sources. Hijnen et al. reviewed the relative UV sensitivity of seeded and environmental (wild) micro-organisms, and inflated doses required for a given log removal of the seeded organisms by a factor, unspecified for individual bacteria but typically 3, to account for the lower sensitivity of the wild microorganisms.

2.5. Revisiting the technical manual

The Technical Manual (Scottish Executive, 2006) provides advice to those who may be responsible for a private water supply. Those sections of the manual relating to water quality and treatment, including UV, originate from an earlier document, Jackson *et al*. (2001), prepared for the UK government, and have been used in the Technical Manual without modification. The text is equivocal in relation to the effectiveness of UV for *Cryptosporidium*, stating that 'certain forms of UV treatment may be successful', and that 'there is evidence that UV is effective in inactivating *Cryptosporidium* provided a sufficient dose is applied'. This text represented the understanding at the time, but was out of date by the time the Technical Manual was published. As described by Bolton and Cotton (2008), prior to 1998 it was generally accepted that UV was ineffective for treating protozoan oocysts. Experimental results showing that *Cryptosporidium* is in fact sensitive to UV were presented in 1998, and this was confirmed by numerous other studies over the next few years. In 2006 UV was recognised as a best available technology for *Cryptosporidium* disinfection in US drinking water quality legislation.

Also, the then current NSF/ANSI 55 standard referred to by Jackson *et al*. (2001), which dated from 2000, specified a target UV dose of 38 mJ cm^{-2}, and this value is included in the Technical Manual. However, NSF/ANSI 55 – 2000 was superseded in 2002 by NSF/ANSI 55 – 2002, in which the target UV dose was increased to 40 mJ cm^{-2} to be consistent with 'international standards'.

2.6. Conclusions

With regard to water quality:

1. Knowing the minimum UV transmittance (UVT) of a water source is essential for UV disinfection applications to ensure the target dose can be applied.

2. The relationship between colour and UVT is not absolute, but 20 ^{o}H likely represents the maximum colour for practical application of UV disinfection.

3. The limited literature available suggests that 4 NTU would not be expected to compromise UV disinfection performance; regardless, it is still desireable to keep NTU to a minimum and would recommend pre-filtering prior to UV disinfection.

With regard to reactivation:

1. From the available information, reactivation is unlikely to be an issue provided a sufficient UV dose for disinfection is applied.

With regard to current standards:

1. Of the current standards relating to validation of UV units for disinfection, the NSF/ANSI 55 – 2012 standard (Class A) is, in principle, the most relevant for the small-scale units likely to be installed for the primary disinfection of private supplies. This standard requires validation by biodosimetry of a UV dose of 40 mJ cm^{-2}.

With regard to UV units currently installed, or available for, private water supplies:

1. Small UV units suitable for single-household use are unlikely to have validation to a recognised standard.

2. Such UV units are often rated for a dose of 30 mJ cm^{-2}. Although this dose is referred to in sales literature variously as a ‘standard’ or ‘protocol’, the basis for so doing is not clear. There is no apparent justification for recommending a rated dose of less than that required for public water supply applications, 40 mJ cm^{-2}.

3. Research Monitoring of PWS

3.1. Study design

Thirty-four Type B supplies across Scotland with existing UV disinfection treatment were selected, characterised and monitored for key water quality parameters quarterly over the course of one year. A subset of six of the above sites which appeared to well-maintained were sampled on a monthly basis.

3.2. Site selection

Locations of sampling sites are shown in Figure 3.1.

The intention was to investigate a set of supplies representative of Type B PWS in Scotland. This selection was made using the data available provided to the project by Scottish Government (DWQR annual returns) and Local Authorities. From initial analysis of these data, it soon became apparent that a truly statistically representative sample for all the parameters of interest was well beyond the resource available to this project. Instead, a more pragmatic site selection procedure was developed as described below.

Site selection was primarily based on Scottish Government datasets because there were some difficulties in combining LA datasets into one database (different formats etc.). Instead, Local Authority data were used to drill down for further detail associated with the selected sites. Where LAs specifically suggested sites that may be of interest, or were of specific interest to the Steering Committee, we incorporated those into our list of prospective sites.

The first sift of site selection was carried out by sorting 2010-2012 Scottish Government data into sites with disinfection “DF” (as sites were required to have UV treatment installed in order to be part of the study) and then sorting those sites with disinfection further into those that had failed to meet standards during 2010-2012.

These were then further sorted into those which had failed for parameters that we felt were of particular interest in terms of affecting UV efficacy.
These were:

- Colour
- Turbidity
- Manganese
- Iron

- Copper (also included as this is known to have an antimicrobial effect that may confound results).

Sites failing for one or more of these parameters were collated into a list. As this list comprised only 61 sources, this was then supplemented by those sites suggested by LAs or SW to give a total of 70 sites. Further sifting on the actual concentrations of these parameters was not deemed to be appropriate as we were unlikely to get a 100% response rate, in particular as we did not know whether DF represented solely UV disinfection. Without any deliberate bias towards LA areas, this actually generated an inherent bias towards Aberdeenshire samples which coincidently worked well in terms of project logistics.

Some sites identified were not feasible to monitor due to their remoteness, in particular where sampling could not be combined with multiple other sites. These were filtered out through discussions with LA representatives on the Steering Committee. In some cases, it was possible to regularly sample remote sites with assistance from the LA.

A further sort of all sites with disinfection treatment was then carried out to identify sites that had been sampled in the last three years but were not recorded as having failed for any of the parameters associated with UV interference. A random subset of these, representing each LA area, was selected because it is important not only to have failing sites but also some which appear to be working effectively. However, again, some of the geographically outlying sites were removed from the selection to provide a final list of 34 non-failed sites.

This yielded an overall list of 104 sites from which to request volunteers for monitoring. A small number of supplies (~ 6) involved in past PWS work carried out at JHI were resampled, giving us a further selection of sites with which to supplement the initial list should the response rate be poor. The final quarterly and monthly sampling sites are detailed in Figure 3.1 - **Error! Reference source not found.** below.

A small number of sites (n = 2) were removed from the list as the project progressed due to events outwith the control of the project team such as change of ownership of the property. Sites lost beyond the first quarter were not replaced as it would not have been possible to gather a full dataset from a replacement supply.

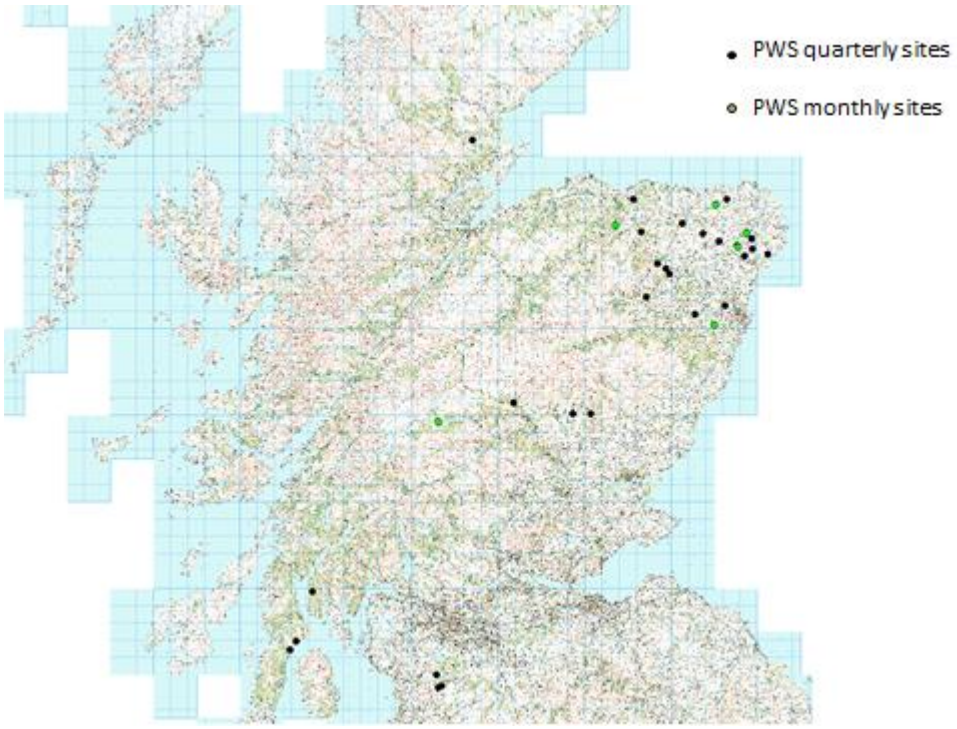

Figure 3.1 Locations of all quarterly and monthly sampling sites

3.3. Data collection

At each of the sampling sites, the following were carried out on the first visit:

- A questionnaire tool was administered, preferably via face-to-face interview
- An adapted version of the PWS risk assessment was completed
- Water samples were taken from the source, i.e. the raw pre-treated water
- Water samples were taken from the treated water, i.e. usually the tap water
- Soil samples were taken from around the source

34 sampling sites were re-visited every quarter. On each occasion, water sampling was repeated and any changes to the treatment system or source (e.g. improvements in source protection) were noted.

A subset of 6 of the above sampling sites was visited on a monthly basis. Again, on each occasion, water sampling was repeated and any changes to the treatment system or source were noted.

3.3.1. Questionnaire

Questionnaire development

A questionnaire was developed in October 2013 with the aim of better understanding the participant's water supply from their point of view. In summary, we wanted to find out how each supply in the study is used, and to also understand any factors that might affect how well the UV treatment system works. The process of interview was also used to establish location(s) of source(s) and treatment system(s), and how the treatment system(s) operated and what instrumentation/products were being used. With permission from the participant, photos were also taken of both treatment system(s) (to aid in the identification of products/instruments being used) and source(s) (to aid in validation of risk assessment evaluations).

The questionnaire was developed primarily to be administered via face to face interview, and a protocol for administration was developed alongside the questionnaire (See Appendix 7.1). It was also recognized, however, that it may not always be possible to administer the interview face-to-face. Due to this a separate self-reported questionnaire was also developed, which participants could fill in on their own. The wording of the questions in these two versions of the questionnaire was different to:

1. Minimize bias – either as a result of the interviewer posing questions in a leading way, or through leading text/questions
2. To minimize discrepancies between how we would expect a single participant to answer a given question regardless of the version of the questionnaire administered

All participants were required to sign a permission slip prior to taking part in either questionnaire which also covered permission to carry out water sampling.

Both questionnaires contained the same number of questions spread over the following three sections:

A. Questions on the type(s) of supply used by the participant and how the source(s) of water are used, if the participant is aware of any factors that may affect the supply (both in terms of quality and quantity).
B. Questions regarding the treatment system (if any), and the maintenance of this system. This section involved establishing what treatment equipment is present and the state of repair that it is in; and who is responsible for maintenance and how often maintenance occurs.
C. The final section addressed interaction with the treatment system other than routine maintenance. This includes the use of pre-treated water.

Questions were developed in conjunction with the Steering Committee. Where possible, and in order to minimize known sources of bias, previously validated questions were used/adapted from other published questionnaire surveys. It was important that the questions posed returned the answer expected from a particular participant. To help ensure this, draft-phase questionnaires were piloted amongst James Hutton Institute staff with PWS in order to identify any ambiguities or inconsistencies.

The final questionnaire and protocol can be found in Appendix 7.1.

Questionnaire administration

In the majority of cases, the questionnaire was administered via face-to-face interview. The interviewers followed a strict protocol and were briefed in how the interview should be handled. All participants were reminded of the study by showing them a copy of the invitation letter. All participants were also informed that all information gathered would be handled anonymously.

It was important that interviewers did not bias respondents into immediately thinking that we were interested in bacterial fails or other aspects of water quality/safety, so interviewers avoided talking directly about these issues or about UV treatment until after the questionnaire had been administered. In all cases, and by way of introduction, the interviewer preceded the interview with the following statements designed to minimise the biases described above:

"As part of a large project looking at use of private water supplies in Scotland, we're interested to find out about your water supply and how it is used. This work is funded by Scottish Government and Scottish Water"
"Would you be happy to answer a few questions about your water supply and show us any parts of the supply system that are accessible? This should take about 10 – 15 minutes."

"Would you also be happy if we took photographs of any part of the supply system and some water samples?"

"If you're happy for us to do that, please could you sign this permission slip?"

Interviewers made sure that all questions asked had a response to them, even if this was that the "participant chose not to respond". This was to ensure that there were no missing data, or ambiguous blank responses.

3.3.2. Risk assessment

Adaptation of current risk assessment
It became apparent that in many cases the original risk assessment developed as part of the 2006 legislation was not being routinely used. Instead, many LAs had adapted this to suit their needs. Primarily this had resulted in a simplification of the original assessment as most LAs reported finding the original assessment as being overly complex and difficult to implement.

Therefore, as part of this project, we collated currently-used risk assessment protocols and pro-forma from all Scottish LAs. These were reviewed. While it was clear to see that many of these assessments were based on the same questions present in the original assessment, the adaptations towards simplification had diminished the purpose; i.e. the ability to assess risk, rather than just the present situation had in most cases been significantly reduced. This is not a criticism of the LAs who are clearly dedicated to improving PWS quality; it is more an indication that the original risk assessment may not be fit for purpose or too challenging to implement.

It was eventually decided to use the original risk assessment as designed to ensure no bias towards supplies which had been risk-assessed using a particular LA pro forma and because there was no obvious “correct” version of the risk assessment currently being used by the various LAs involved in the project. On using the risk assessment in the field, the project team also found limitations in implementation due to the complex nature of the assessment. Therefore we also ended up using a simplified version of the risk assessment and it might be worthwhile re-visiting the design of the assessment in the future. The risk assessment protocol may be found in Appendix 7.3.

Implementation of risk assessment on-site
After completion of the questionnaire, the interviewers carried out the risk assessment as independently as possible with minimal input from the participant. However, where necessary, the answers gained during the questionnaire interview were used to inform the risk assessment.

The tables appropriate to the type of water supply being assessed (well, surface, borehole, etc.) were selected (see Appendix 7.3). There were two tables for each type of supply:

a. A general site survey
b. A supply survey

For each question of the risk assessment, the interviewer determined if the answer was yes, know or don’t know and the corresponding risk category (high, medium, low) was circled in the table.

For each question, the interviewer then determined a likelihood category. Due to the practicalities of the assessment, and the fact that the interviewer is unlikely to have all the information required, a pragmatic approach was adopted with the interviewer going with their best informed judgment. It was agreed that interviewers should spend no longer than a minute or two on each question, and should go with their expert judgment. Where selection of likelihood category was extremely difficult, the interviewer could seek additional information from the participant. If this was done, a note of this was made in the margin of the risk assessment pro-forma.

Once all the questions had been answered, a GPS device or OS map was then used to capture the National Grid Reference of the source and supply. The interviewer also photographed the layout of the system(s) and added any other notes of interest (e.g. deer seen close to storage tanks).

The remaining information, including the determination of the final risk score was completed back at the James Hutton Institute. This was to ensure accuracy of calculations made, i.e. all calculations were made in the office rather than in the field where there is increased potential for error.

3.3.3. Water sampling and analyses

Water sampling protocol
All water samples were analysed within 6 hours of collection with the exception of a small number of sites where logistics/owner availability dictated otherwise. In those cases, samples were analysed within 12 hours. All standard water analyses were undertaken by Scottish Water laboratories which are accredited to the UKAS standard “Drinking Water Testing Specification Accreditation Requirements for Sampling and Testing in Accordance with the Drinking Water Testing Specification (DWTS)”

Samples were taken by research assistants employed by the James Hutton Institute who underwent project-specific training following discussion of sampling approaches with the Steering Committee.
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All sampling bottles were supplied by Scottish Water pre-labelled, sterilised and sealed. Sample bottles were only used if the seal was in-tact as an indicator of sterility. Water sampling was carried out according to a modification of the protocols used by Scottish Water.

Tap samples –

1. The tap to be sampled (domestic cold water tap) was cleaned around and as far up the inside as possible with disinfectant wipes.

2. The cold water tap was then run for 2-3 minutes before the sample was taken.

3. All sampling bottles were treated as aseptically as practicable; samplers avoided touching the inside of bottle caps and bottles so as not to compromise sterility.

4. All sample bottles were filled completely to ensure that there was no air trapped inside the bottle when sealed.

5. Sealed, full bottles were placed in a cool box for transportation to the nearest Scottish Water sample drop-off point.

Source samples –

1. Where the source was difficult to access directly, a baler was used to remove the sample from the source and water was aseptically expelled into the sample bottle. Balers were cleaned (sterile water) and surface sterilised inside and out with 70% ethanol between samples and received a final rinse with sterile water.

2. All sampling bottles were treated as aseptically as practicable; samplers avoided touching the inside of bottle caps and bottles so as not to compromise sterility.

3. Samples were taken from the headworks reservoir containing the raw source water (that is, before the water passes through filters etc.)

4. All sample bottles were filled completely so that there was no air trapped inside when sealed.

5. Sealed, full bottles were placed in a cool box for transportation to the nearest Scottish Water sample drop-off point.

Water analyses

The following water analyses were undertaken on all samples (Table 3.1)

Table 3.1 Water analyses undertaken on all samples within this project. All water analyses were analogous to those undertaken by Local Authorities when assessing a PWS; as such bacterial counts on source water samples were presumptive while all bacterial counts on tap water were also subject to confirmatory tests.

Parameter	Scottish Water Method ref.
Colony count at 22 °C (cfu ml^{-1})	E/M D03
Colony count at 37 °C (cfu ml^{-1})	E/M D03
Presumptive coliforms (cfu 100 ml^{-1})	E/M D08
Presumptive *E. coli* (cfu 100 ml^{-1})	E/M D08
Presumptive *Clostridium perfringens* (cfu 100 ml^{-1})	E/M D05
Presumptive *Enterococci* (cfu 100 ml^{-1})	E/M D04
Colour (mg l^{-1} Pl Co^{-1})	E/GIC003/IC002/IN
Conductivity (µS cm^{-1} at 20 °C)	E/GIC003
Hydrogen ion (pH)	E/GIC003/IN 37
Total organic carbon (mg C l^{-1})	E/D45.1
Total organic carbon (filtered) (mg C l^{-1})	E/D45.1
Turbidity (NTU)	E/GIC003/IN 33
UV Transmittance (%)	E/IC016 (#)
Aluminium (µg Al l^{-1})	E/ICPOES1/GIC001
Iron (µg Fe l^{-1})	E/ICPOES1/GIC001
Manganese (µg Mn l^{-1})	E/ICPOES1/GIC001

3.3.4. Soil sampling and analyses

Soil sampling protocol

Soil samples (0 – 15 cm) were taken from around the source (i.e. wellhead) using a screw augur. Soil samples were taken during the first visit to each of the sampling sites during the risk assessment and walk over. The exact sampling design in terms of location and number of samples was site dependent; the aim was to sample from soil likely to have an

influence on the quality of the supply. In most cases samples were taken from soil immediately 'upstream' of the source.

Soil analyses and interpretation of data

The following soil analyses were undertaken on samples from 28 of the monitoring sites where land around the source was readily accessible and supply owners agreed to soil samples being taken. Where possible, samples were obtained at each quarter. Coliform counts from soils were log transformed and subjected to analysis of variance (Genstat 17) to determine the effects of sampling time (quarters 1-4) and were also categorized into very low, low, medium and high classifications for discussion (Table 3.2):

Table 3.2 Soil analyses undertaken within this project

Parameter	Method
Moisture (%/w)	Oven at 105 °C (limit of detection 0.00043 g)
Loss on Ignition (%/w)	Furnace at 450 °C (limit of detection 0.00043 g)
Particle size distribution	Samples dispersed and analysed by laser diffractrometry (Mastersizer, Malvern Instruments, UK)
Total coliforms and *E. coli* (CFU/g dry soil	Approx. 5g fresh soil was dispersed in 15 ml sterile ¼ strength Ringer's solution (Oxoid, UK), diluted 100-fold and used as inoculum for Most Probable Number (MPN) analyses (Colilert, IDEXX, UK)Counts were calculated on the basis of dry weight equivalent of soils. Detection limit: 3 CFU/g.

3.4. Results

3.4.1. Questionnaire

From an initial sub-set of 37 properties, 33 completed questionnaires were returned (89 % response rate). Each time the sampling team re-visited a property (monthly or quarterly sampling) they asked the respondents if there were any changes to their responses since the previous sampling period. Where responses had changed, each new visit was

recorded as a new questionnaire entry. This means that for some questions there may be a total of responses > 33.

The questionnaire contained a series of 41 questions under three section headings (Sections A, B and C – see Appendix 7.1). While all questions are summarised below, it is not the intention to present the detailed responses to all 41 questions in this section. Specific details have been presented (see Table 3.3 to Table 3.9) where questions (or responses to questions) were most pertinent to the aims and objectives of this study.

Section A – Supply and use

This section of the questionnaire asked about the respondents' water supplies, who uses them, and how they are used.

The majority of respondents had lived in the property of interest for more than 9 years, although this ranged from 2 to 43 years. On average, 2.7 people lived in the property of interest (range from 1 to a maximum of 7 inhabitants). All respondents knew who their water supply served; 57 % reported that their water supply served another property, while 43 % recounted that their supply was for the sole purpose of the property of interest. All respondents knew who had the responsibility for maintaining their water supply, in the majority of cases this was the owner (or shared ownership) of the supply. A total of 82 % of respondents knew where their water supply came from, 8 % reported that they were not sure, and a further 8 % that they did not know. A further 2 % stated that they did not know if they knew where the water supply came from. There was significant variation in how the respondents described the quality of their drinking water (Table 3.3); however, generally speaking 61 % of respondents reported having 'good' or 'very good' drinking water quality, with the remaining 39 % generally having some complaints about their water quality.

Table 3.3 Summary of responses returned in the questionnaire to the question "How would describe the quality, appearance and taste of your drinking water?"

Description of quality	Frequency	Percentage	Cumulative percentage
No response	1	2.94	2.94
Acceptable, good colour	1	2.94	5.88
Adequate	1	2.94	8.82
Bad appearance yellow/brown	1	2.94	11.76
Brackish after rain, bit flat tasting	1	2.94	14.70
Fairly heavy peat supply, pale colour normally	1	2.94	17.64

Description of quality	Frequency	Percentage	Cumulative percentage
Good	4	11.76	29.40
Good but does turn sink blue	1	2.94	32.34
Good with filters, but coloured otherwise	2	5.88	38.22
Improved since sand filter system installed. Not so coloured and gritty after rain	1	2.94	41.16
Looks fine, usually tastes and smells fine	1	2.94	44.10
Quality is OK, taste is OK, highly coloured particularly after rain, winter less coloured as land frozen up	1	2.94	47.04
Varies, 6 months dark brown – undrinkable. November - March clearer. 9 months ago started collecting rain water to drink	2	5.88	52.92
I use bottled water	1	2.94	55.86
Clear, but brown after rain. I drink bottled water only as don't like the water	1	2.94	58.80
Clear, good water	2	5.88	64.68
Doubtful quality, good appearance	3	8.82	73.50
Filter jug water clear, good taste	2	5.88	79.38
Good taste and colour	2	5.88	85.26
Slight taste but good appearance	1	2.94	88.20
Taste of iron	1	2.94	91.14
Very good	2	5.88	97.02
Very good, no colour	1	2.94	100.00

Overall, about a third of respondents reported that they did not detect any changes in supply throughout the year, while 36 % reported that their water became more coloured (and in some cases stronger in taste also) after heavy rain or snow (Table 3.4).

Table 3.4 Summary of responses returned in the questionnaire to the question "Do you notice any changes in your water? And if so, when does this happen?"

Description of changes to water, and when this occurs	Frequency	Percentage	Cumulative percentage
No changes	11	33.33	33.33
After rain it is brown	12	36.36	69.69
Brackish after rain and deposits occur before the Mn filter	1	3.03	72.72
Brown once in 5 years - flooding	1	3.03	75.75
Lack of servicing leads to discolouration	1	3.03	78.78
Ochre in water supply produces sludge	1	3.03	81.81
Green hair!	1	3.03	84.84
Summer very brown, winter lighter brown	2	6.06	90.90
UV installed, drink bottled water	1	3.03	93.93
Odour depending on dry or wet period	1	3.03	96.96
Only if use surface supply, twice in 7 years	1	3.03	100.00

Respondents were asked about their concerns regarding their supply and the main responses to this question can be seen in

Table 3.5. Other responses included: concerns regarding bacterial and pesticide contamination (n = 1); contaminated soil deliberately introduced to water (n = 1); contamination from cattle (n = 2); breakdown of filters and UV system (n = 1).

Table 3.5 Summary of main responses returned in the questionnaire to the question "Is there anything about your water supply that concerns you?"

Description of concern	Yes (%)	No (%)	Don't know (%)	Total (%)
Risk of flooding	4.05	88.31	3.90	96.26
Risk of contamination	42.86	53.25	3.90	100.00
Risks to health from drinking	29.87	70.13	0.00	100.00
Risk of supply being interrupted	44.16	55.84	0.00	100.00

Respondents were asked about whether the supply had been tested (recently) and if testing had occurred, if they knew what the results had shown. This was an open question and resulted in 29 different responses, 27 of which had had the supply tested and did know the results. Of these 17 (63 %) reported that their water had failed on one or more parameter during this testing, but of these only 4 respondents specifically mentioned bacterial fail. The majority of respondents could not remember the exact cause(s) of the fail, but simply described the water as being 'bad'.

Respondents were then asked to describe what the land around the source is used for and if they had seen any wildlife in that area. Again, there was a variety of different answers; however the majority of sources were located in land used for either agriculture, forestry, or for equestrian purposes. Wildlife reported as having been seen included rabbits, deer, badgers, mink, foxes, pheasants and grouse. A number of respondents considered garden ground or grazing land to have "no wildlife". Respondents were also asked how often they saw animals (of any type – livestock, domestic, wildlife) access the area close to the source of their supply. Just under a third of respondents reported that wildlife could "never" access this area, with a similar response rate for "sometimes" or "often"; only 13 % indicated that animals could access the area around their source "all of the time" (

Table 3.6). The majority of respondents reported that animals could access right up to the source of their water, with one respondent reporting that they could "*stand in it, swim in it,*

die in it!". A smaller number indicated that there was some form of fencing around their source, but in most cases this provided a buffer zone of less than 1 or 2 meters.

Table 3.6 Summary of responses returned in the questionnaire to the question "How often do you see animals (livestock, domestic, wildlife) access the area around your water source of where the supply is?"

Frequency of animals close to source	Percentage positive responses (%)	Cumulative total (%)
Never	29.07	29.07
Sometimes	23.26	52.33
Often	27.91	80.24
All the time	12.79	93.03
Don't know	6.98	100.00

Respondents were asked about what they used the water from their PWS for. While all respondents used the water for cooking and cleaning, only 80 % used it for drinking and 97 % used it for washing (Table 3.7). Half of all respondents used the water for watering animals. Of these, 54 % used this water untreated. On the whole, these people were using only small volumes of water to fill e.g. a couple of troughs each week. However, one respondent was using in excess of 270 l d^{-1} between May and November for large-scale animal watering. About 14 % of respondents reported using their water for irrigating plants (including crops) and two thirds of these individuals used this water untreated all of whom reported using in excess of 200 l d^{-1}.

Table 3.7 Summary of responses returned in the questionnaire to the question "what do you use your supply for?"

Description of use of the water	Yes (%)	No (%)	Total (%)
Drinking	79.55	20.45	100.00

Description of use of the water	Yes (%)	No (%)	Total (%)
Washing	96.59	3.41	100.00
Cooking	100.00	0.00	100.00
Cleaning	100.00	0.00	100.00
Watering animals	50.00	50.00	100.00
Irrigating plants	13.64	86.36	100.00
Other uses	0.00	100.00	100.00

Section B – Treatment and maintenance

This section of the questionnaire asked questions about whether respondent's water was treated and the type of treatment system they had. It also asked about routine maintenance of their system, how often this took place, and who carries it out.

All respondents (100 %) reported that their water underwent some form of treatment. The majority of treatment systems had been installed within the last 5 – 15 years, although one dated from as early as 1971. While many of the treatment systems reported contained similar components, there were many system-specific variations as well as variability on how respondents described similar pieces of apparatus. These descriptions provide an insight into the variability of understanding that the respondents have regarding their water treatment systems. Table 3.7 summarises all the various descriptions of the treatment systems. At this point, the interviewer also took photos of the treatment system.

Table 3.8 Summary of responses returned in the questionnaire to the question "Can you describe the treatment system you have?"

Description of treatment system	Frequency	Percentage	Cumulative percentage
20 µm filter, UV, pH, and then into header tank	1	3.23	3.23
25 µm bag filter, 10 µm 10 inch filter, carbon filter and UV tube	1	3.23	6.46
5 µm micron, carbon filter, UV, Fe filter	1	3.23	9.69
Arsenic, Fe, Mn, ion exchanger, UV filters	1	3.23	12.92
Burn water – between header tank and house: 50 µm mesh, 5 µm filter, UV (spun wound). Rain water – 350 gallon tank: from roof to gutter mate,	2	6.45	19.37

Description of treatment system	Frequency	Percentage	Cumulative percentage
mesh filter, nylon filter mesh.			
Clean out tank once a year and UV filter	1	3.23	22.60
Course, fine filter, pH correction, UV, pressure vessel (?)	2	6.45	29.05
Fe and Mn filters, UV, pH correction	1	3.23	32.28
Filter, pH, and UV	1	3.23	35.51
From settlement tank 5500 l through 30 µm filter then 5 µm filter then UV filter	1	3.23	38.74
Mn filter, ? µm filter, UV, Pumped from well to holiday cottage tank then down to (owners) house	1	3.23	41.97
Pressure tank, filter, pH correction then UV	1	3.23	45.20
Pressure vessel, filter, sand, possible pH, 5 – 10 µm filter and UV	1	3.23	48.43
Pump to accumulator tank, 20 µm filter, 5 µm filter, UV bulb to softener balls to house	1	3.23	51.66
Pump. Chlorine before holding tank. 20 and 5 µm filter at property level and UV	1	3.23	54.89
Sediment filter, UV filter, CO_2 filter,	1	3.23	58.12
Source pumped to ground level tank, through filter and UV, then into roof space tank	1	3.23	61.35
Standard general filter, large cylinder for Mn removal, UV lamp	1	3.23	64.58
Through 2 filters, UV and into taps	1	3.23	67.81
UV filter, 50 µm filter, then to tap	1	3.23	71.04
UV, secondary filter	1	3.23	74.27
UV, storage cupboard	1	3.23	77.50
Chalk and sand filters, micron filters then UV	1	3.23	80.73
Cotton filter, pH and UV	1	3.23	83.96
Header tank, pump, ? filter, pH filter, element filter,	1	3.23	87.19

Description of treatment system	Frequency	Percentage	Cumulative percentage
UV			
Media filter, 5 μm, UV, pumped for pressure	1	3.23	90.42
One filter then UV bulb	1	3.23	93.65
pH correction, aerator to drop out the iron, iron filters, organic scavenger with a brine backwash, then through a carbon filter and a 5 μm filter, then UV	1	3.23	96.88
Pre filter, UV bulb, pH crystals, 5 μm filter	1	3.23	100.00

Roughly 42 % of respondents reported having their treatment systems serviced on a regular basis, with 16 % of these individuals having their system serviced at least every 6 months and 52 % having their system serviced every year. At the other end of the scale, almost 20 % had their systems serviced less frequently than once every 5 years. No respondent reported having never had their system serviced. Over 75 % of respondents who had their systems serviced on a regular basis reported servicing the system themselves, and most respondents reported opening parts of the treatment system for small cleaning or maintenance jobs even if they were not able/comfortable performing a full service. 78 % of respondents reported that it was very important to them to have a working water treatment system (3 % claimed it was not at all important to them). Reasons for why this was important primarily included health, usually of young children or of tenants in rental/holiday properties. Few respondents seemed overly concerned about their own personal health with respect to the quality of the water supply and only 30 % reported seeing or tasting differences in their water supply immediately after the system had been serviced.

Section C – Interaction with the treatment system

This section of the questionnaire was concerned with how individuals used their treatment systems and if there were any circumstances that caused them to do anything different with their system.

All respondents (100 %) reported that they leave their treatment system switched on all the time, and 74 % reported that they could tell if the treatment system had failed. While some respondents reported that failure was indicated by a noticeable drop in water quality, the majority (> 85 %) stated that they relied on warning lights or alarms as the indicator. Despite this only 25 % stated that they did anything differently during a system fail such as

a power cut. These individuals were primarily responsible for tenanted properties or holiday accommodation. Remedial measures included dosing tanks with chlorine tablets and running taps for a while to remove any untreated water from the system once the chlorine had been added or once the power supply was restored (Table 3.9). About 40 % of respondents also reported taking pre-treated water from their system for various purposes. The majority of respondents used this water for irrigating plants or watering animals, although one individual used it for flushing an outside toilet, one for washing vehicles, and one person reported using pre-treated water for all purposes (including drinking, but would boil) when their supply was running low.

Table 3.9 Summary of responses returned in the questionnaire to the question "With regards to your water supply, do you do anything differently during or following a power cut?; If 'yes', could you tell us what you do?"

Description of remedial action in the event of a failure in power supply	Frequency	Percentage	Cumulative percentage
Dose tanks with chlorine	2	14.29	14.29
Boil water	1	7.14	21.43
Run taps to remove un-treated water	3	21.43	42.86
Inform guests/tenants	2	14.29	57.15
Stop using the water	1	7.14	64.29
Re-set all switches	3	21.43	85.72
Check UV and other filters	2	14.29	100.00

3.4.2. Risk assessment

The results of the risk assessment are shown in Table 3.10. The existing risk assessment approach is weighted so that if a single factor is identified as being of "high risk", then the entire supply is labelled as being at high risk of bacterial failure. This means that nearly every assessment will return a verdict of "high risk". In this study, all 37 sites (apart from ID 14 where land access issues meant that the risk assessment could not be undertaken) were identified as being at "high risk". For data analysis purposes, we documented the number of factors scored as "high risk" for each supply (Table 3.10). No obvious relationships between the number of high risk factors and frequency of bacterial fails were observed.

Table 3.10 Summary of results of site-specific risk assessments in relation to bacterial fails

ID	No. high risk factors	No. quarterly bacterial fails	No. monthly bacterial fails
1	3	1	
2	4	0	
3	3	3	
4	4	1	
5	8	0	
7	14	0	
8	10	1	
9	9	2	
10	9	1	
11	4	0	
13	1	0	
14		2	3
15	7	0	
17	4	0	1
18	7	4	13
19	5	0	1
20	4	0	
21	6	0	
23	12	1	
24	6	0	

25	6	0	
27	2	0	
28	4	2	
29	3	0	
30	8	1	
31	4	1	
32	8	1	2
33	11	0	
34	11	0	
35	15	0	
36	11	0	
37	11	0	0

3.4.3. Water quality

The entire quarterly monitoring data set was initially summarised in terms of water quality, highlighting where individual water supplies had failed either due to bacterial counts or due to exceedance of standards for chemical parameters (Table 3.11). Following on from this, a more detailed descriptive analysis was undertaken for all those water supplies that consistently passed microbiological and chemical standards (Table 3.12), as well as those that consistently failed (Table 3.13).

Table 3.11 Overview of all sampling sites with indication of microbial and chemical passes (P) and fails (F). All fails are highlighted; ■ represents minor microbiological fails (1 CFU $100ml^{-1}$ detected); ■ represents more significant microbiological fails (above 1 CFU $100ml^{-1}$ detected); ■ represents a chemical fail.

Site ID	Micro Pass (P)/F ail (F)				Chemical Pass (P)/ Fail (F)			
	Q1 (Oct-Dec)	Q2 (Feb-Mar)	Q3 (May)	Q4 (Aug)	Q1 (Oct-Dec)	Q2 (Feb-Mar)	Q3 (May)	Q4 (Aug)
1	P	F	P	P	F	P	F	F
2	P	P	P	P	F	P	F	P
3	F	P	F	F	F	F	F	F
4	F	P	P	P	F	P	P	P
5	P	P	P	P	P	P	P	P
7	P	P	P	P	F	P	F	F
8	F	F	P	P	F	F	F	F
9	P	P	F	F	F	F	F	F
10	P	P	F	P	F	F	F	F
11	P	P	P	P	P	P	F	F
12	P	*	*	*	P	*	*	*
13	P	P	P	P	P	F	F	F
14	P	F	F	P	P	P	P	P
15	P	P	P	P	P	P	P	P
17	P	P	P	P	P	P	P	P
18	F	F	F	F	F	P	F	F
19	P	P	P	P	F	F	F	F
20	P	P	P	P	P	F	P	P
21	P	P	P	P	P	P	P	P
23	P	P	F	P	F	P	F	P
24	P	P	P	P	P	P	P	P
25	P	P	P	P	P	P	P	P
26	F	P	P	P	P	F	P	P

27	P	*	*	*	P	*	*	*
28	P	F	P	F	P	P	P	P
29	P	P	P	P	F	F	P	F
30	P	F	P	P	P	F	P	F
31	F	P	P	P	F	F	F	F
32	P	F	P	P	F	F	P	P
33	P	P	P	P	P	F	F	P
34	P	P	P	P	P	F	F	F
35	P	P	P	P	P	P	P	P
36	P	P	P	P	P	P	P	P
37	P	P	P	P	P	F	F	P
% fails	**13.5**	**23.0**	**20.0**	**14.2**	**37.8**	**43.0**	**45.7**	**40.0**

Table 3.12 In-depth description of all sites highlighted in Table 3.11 as consistently passing microbiological and chemical standards

Site ID	Water Treatment Description	Type of Supply	Soil Characteristics	Catchment Type	Appearance of Treatment system on first visit	System age and maintenance	Source water quality
5	Media filter, 5 µm filter; UV disinfection.	Spring	Sandy loam; 17.5% OM; low coliforms	Rough Grazing/ Moorland	Tidy, professional installation filters not viewable	Installed 6 years ago; Serviced annually and owners change filters 6 monthly.	Low pH. Low turbidity, TOC and colour. Can have high Fe and Al and moderately high Mn. High UV transmittance >95 %.
15	Filter (not specified); pH correction; element filter (no detail given); UV disinfection	Well	Sandy loam; 14.5 % OM; low coliforms	Forestry/ Woodland	Tidy, professional installation; filter clean	Installed 1 year ago. Serviced annually and owners maintain 6 monthly.	Very low pH, Low turbidity, TOC and colour, low metals. Fairly high UV transmittance >85 %.
17	Filter (not specified); UV disinfection	Borehole	Sandy silt loam; 3.5% OM; low coliforms	Arable	Borehole muddy; filter brown; generally tidy; Professional installation	Installed 4 years ago. No professional servicing; owners change filters and bulbs annually.	Variable pH (low-neutral), Low turbidity, TOC, colour , low metals. Fairly high-high UV transmittance >80 % but usually > 95 %.
21	Filter (not specified; appears coarse), correction; UV disinfection	Well	Sandy silt loam; 12.5 % OM; medium coliforms	Arable/garden	Tidy, professional installation; Filter brown	Installed 2 years ago. NO professional servicing; owners change filters and bulbs after 2 years and pH granules after 3 years.	Low pH. Low turbidity, TOC, colour, low metals. Fairly high UV transmission ≥85 %.

Site ID	Water Treatment Description	Type of Supply	Soil Characteristics	Catchment Type	Appearance of Treatment system on first visit	System age and maintenance	Source water quality
24	Coarse filter, fine filter (not specified); pH correction; UV disinfection	Well	Loamy sand; 0.5 % OM; very low coliforms	Arable/garden	Tidy, Plumber installation/professional parts ; filters brown	Installed 2 years ago, No professional servicing, owners change filters, bulb and pH granules annually.	Low pH. Low colour, moderate TOC. High turbidity, high Fe, moderate-high Mn, high Al. High UV transmission > 90 %.
25	Pre-filter; UV disinfection; pH correction; 5 µm filter	Well	Sandy silt loam; 9.3% OM; low coliforms	Arable	Tidy, Plumber installation/professional parts ; filters brown	Installed 4 years ago. No professional servicing, owners change filters and bulb annually; pH granules every 2 years.	Low pH, generally low colour, TOC, turbidity, metals but can spike to moderate levels. UV transmittance usually high; can drop to ~ 70 % when other parameters spike (Q4).
35	UV disinfection; filter (not specified)	Well	Sandy loam; 9.2% OM; high coliforms	Grazing	Fairly tidy, professional installation; filter brown	Installed 3 years age. No professional servicing, owners maintain every 6 months with parts from a professional installation company.	Low pH, colour, turbidity, TOC, metals. UV transmission high ≥ 90 %
36	Filter (unspecified; was not mentioned but on photographs) UV disinfection only	Well	Sandy silt loam; 11 % OM; low coliforms	Arable/Rough grazing	Tidy, professional installation; filter clean	Installed 1 year ago. Serviced professionally annually.	Low pH, colour, turbidity, TOC. Generally low metals – Al and Fe can spike to moderate levels (Q4). UV transmission high >95 %.

The eight supplies, six wells, one borehole and one spring, which did not fail during any quarterly sampling (Table 3.12) covered a range of system age from recently installed systems (1 year ago) to older systems (installed 6 years ago). These supplies appeared to be generally well maintained. Six of the treatment systems were installed by professional installers. The remaining two supplies treatment systems were, according to owners, installed by plumbing services, however parts of the system carried recognised professional installer branding and therefore it is not clear whether parts were supplied by a professional installer but the installation was carried out by a plumbing contractor, or whether the information supplied by the owners was incorrect and the system was indeed installed by a professional installer. All eight supplies had at least one filter in line prior to UV disinfection. Three had pH correction. Only one, site 25, had fine filtration (5 µm) following the UV disinfection step. All others had filtration and other treatments prior to the disinfection step. However, site 25 did have a coarse filter prior to the disinfection step. All but one of the eight supplies underwent some form of maintenance at least annually. Three of these supplies were maintained at six monthly intervals. Two of the eight supplies were serviced professionally every year but owners also undertook additional more frequent maintenance. Five of these supplies were never serviced professionally, only by the owners and the remaining supply was serviced professionally each year and owners did not undertake any maintenance.

Supplies were situated on sandy loam (3), loamy sand (1) and sandy silt loam (4) soils with a broad range of estimated organic matter content between 0.5 and 17.5 %. Four of the catchments included or were dominated by arable land and or garden. Three included grazing land (2 rough grazing) and one forestry/ tree cover. The coliform counts from soil in the locality of supply source were low for the majority of supplies, with one classed as medium and one as high.

Broadly, the source water quality of these eight sites is characterised by low pH, low colour, turbidity, TOC, and metals with generally high levels of UV transmittance. In sites 25 and 36, some parameters were seen to spike during quarter 4 (August), which is potentially associated with relatively high rainfall. Site 5 tended to have high source water metal loadings. These factors did not lead to bacterial or chemical fails at the tap and at sites 5 and 36 UV transmittance remained high. It is unclear why the substantial decrease in UV transmittance at site 25, which could be linked to an increase in dissolved organic matter (filtered TOC rose from <1 for Q1-3 to 4.4 mg l^{-1} at Q4) did not lead to microbiological fails as source water contained a substantial loading of coliforms/ *E. coli* (8.7×10^4) and 2×10^2 CFU per 100 ml respectively) in the source water.

The key factors characterising these sites where potable water consistently met quality criteria and UV disinfection appears to be effective are:

- Installations were generally carried out by professionals
- Filtration of some sort – coarse, fine or both is installed prior to UV disinfection

- Filters are maintained and bulbs are replaced at least annually
- Owners tend to be involved in maintenance
- Dominance of arable/garden (non-grazing/upland) catchments
- Generally low soil loading of coliforms.
- Sources waters are low pH, generally low in colour, turbidity, TOC and often low in metals.
- UV transmittance of source water is usually high.

Table 3.13 Characteristics of sites that fail microbiologically: Emboldened Site ID represents sites with more than one microbiological fail within the quarterly sampling dataset. Unless specified, 'high' indicates that the water supply has failed for this parameter at least once during the monitoring campaign.

Site ID	Water Treatment Description	Type of Supply	Soil Characteristics	Catchment Type	Appearance of Treatment system on first visit	System age and maintenance	Source water quality	Tap water quality issues
1	pH correction; aeration and Fe filters to remove Fe; organic scavenger; carbon filter; 5 µm filter; UV disinfection	Spring	Sandy loam; 39.5 % OM; very low coliforms	Rough grazing/ moorland	Tidy, professional installation; filter not viewable	Installed 2 years ago; No professional servicing, owners check dams, tanks, UV lamps, pressure and wash/disinfect filters every 6 months.	High colour, pH low-neutral, TOC, low-moderate turbidity, elevated Fe; moderate Al, Mn. UV transmittance often very low (23-70 %)	High colour (Q3 & 4), low pH, high Fe (Q1,3,4); high Mn (Q4). TOC ranges low-high.UV transmittance ranges from low-high (34-91 %)
3	Chlorination; Holding tank; 20 µm filter; 5 µm filter; UV disinfection	Burn	Sandy loam; 11.8 % OM; medium coliforms	Moorland	Tidy, not professional installation	Installed >40 years ago; UV installed 6-7 years ago. Professional servicing annually.	High colour, pH ~ neutral, low TOC & turbidity, elevated Fe; moderate Al; low Mn. UV transmittance low-moderate (36-67 %)	High colour, TOC and Fe. Low – moderate UV transmittance (39-68 %).

Site ID	Water Treatment Description	Type of Supply	Soil Characteristics	Catchment Type	Appearance of Treatment system on first visit	System age and maintenance	Source water quality	Tap water quality issues
4	Bag filter (25 µm); 10 µm filter; carbon filter; UV disinfection	Surface supply at Q1; Borehole Q2-4	Loamy sand; 6.8 % OM; medium coliforms	Woodland	Tidy, plumber installation; filters very brown	Installed 3 years ago. No professional servicing, maintained by owner annually, changing cartridges & UV lamp.	Colour, TOC, turbidity, metals high for surface supply (Q1). All except Mn low for borehole (Q1-3) – Mn became even higher; pH~ neutral. UV transmittance very low Q1 (23 %) but generally high >85 %.	High colour, TOC and Fe for surface supply (Q1). All chemistry met standards on borehole supply. UV transmittance low (surface supply - 25 %) to high (borehole - 93-95%).
8	Settlement tank; 30 µm filter; 5 µm filter; UV disinfection	Burn	Sandy loam; 6.3 % OM; medium coliforms	Woodland/ Rough grazing	Tidy, professional installation, coarse filter clean, fine filter brown	System installed 2 years ago. No professional servicing, maintained by owner – filters changed every few months, UV bulb replaced every 10 months.	Colour, TOC,Fe and Al high; Mn low; turbidity low. UV transmittance generally low (36-67%)	High colour, TOC and Fe. UV transmittance low-moderate (32-66 %).

Site ID	Water Treatment Description	Type of Supply	Soil Characteristics	Catchment Type	Appearance of Treatment system on first visit	System age and maintenance	Source water quality	Tap water quality issues
9	LIFF water conditioner; UV disinfection	Well	Sandy silt loam; 14.3 % OM; medium coliforms	Grazing	Tidy, plumber installation; filter not viewable	System installed 2 years ago. Professionally serviced annually.	Low colour, pH ~ neutral. Low TOC, turbidity, metals except Mn elevated in Q3 and Q4. UV transmittance high (92-94 %).	High Mn. UV tranmittance generally high (87-91 %) but very low Q1(20%).
10	Two filters (not specified); UV disinfection	Borehole	No data	Grazing	Professional installation; filter not viewable.	Installed 15 years ago. Professionally serviced less frequently than every 5 years. Owners change filters every 2-3 years.	Moderate colour; pH ~ 7-8. TOC, Turbidity low, Al low, Fe and Mn elevated Q1 and Q2. UV transmittance moderate-high (75-80 %).	Elevated Mn throughout, high Fe Q3. UV transmittance high (80-82 %

Site ID	Water Treatment Description	Type of Supply	Soil Characteristics	Catchment Type	Appearance of Treatment system on first visit	System age and maintenance	Source water quality	Tap water quality issues
14	5 µm filter; carbon filter (not fitted); UV disinfection; Fe filter.	Quarry	No data	Woodland	Tidy, professional installation, filter not viewable	System installed 2 years ago. No professional servicing, owners change filters every 6 months and will change UV.	Moderate colour, pH ~ neutral. Low-moderate TOC and turbidity, low Al & Mn. Fe can be elevated (Q3 & 4). UV transmittance moderate (73-76 %).	None
18	Filter; UV disinfection. There was no filtration in use at the time of the initial sampling. In March 2014 (after Q2 sampling), new 30 and 5 um filters, 30 W UV lamp and new quartz sleeve were fitted*.	Burn	Sandy loam; 23.6 % OM; low coliforms	Rough grazing/ moorland	Tidy, plumber installation, filters dark brown.	System installed 2 years ago. Not serviced except as part of this project in March 2014*	High colour, pH low-neutral, high TOC, low turbidity, high Fe, low Mn, moderate Al. UV transmittance low (44-63 %).s	High colour (Q1, Q4), low pH, moderate-highTOC, moderate-high Fe, Mn. UV transmittance low-high (48-81 %).

Site ID	Water Treatment Description	Type of Supply	Soil Characteristics	Catchment Type	Appearance of Treatment system on first visit	System age and maintenance	Source water quality	Tap water quality issues
23	UV disinfection only	Well	No data	Arable/ grazing	Tidy, unknown installer (small under sink unit);	System installed by previous occupier >6 years ago. Not serviced.	Low pH. Low colour, TOC, turbidity, metals. Very high UV transmittance (95-99 %).	Low pH. UV transmittance very high (97-99 %)
26	UV disinfection; 50 µm filter.	Well	No data	Grazing	Unknown installer	System installed by previous occupier 13 years ago. Professionally serviced – filters and UV bulb changed every 6 months.	Low pH. Low colour, turbidity, low-moderate TOC, sometimes high Al and moderate Fe. UV transmittance high-very high (88-97 %).	Turbidity, Al, Fe (Q2 only). UV transmittance high (82-93 %).
28	Sediment filter; UV disinfection; carbon filter	Well	Sandy loam; 13.8% OM; high coliforms	Arable/ grazing	Professional installation; Some staining of pump,filter brown	System installed 3 years ago; professionally serviced every 6-12 months.	Low pH. Low-moderate colour & TOC. Low turbdity, & Mn; Fe and Al can spike to high levels (Q3). UV transmittance very high (93-96 %).	None. UV transmittance high (91-93 %).

Site ID	Water Treatment Description	Type of Supply	Soil Characteristics	Catchment Type	Appearance of Treatment system on first visit	System age and maintenance	Source water quality	Tap water quality issues
30	Chalk and sand filter; filters (not specified); UV disinfection	Well	Sandy silt loam; 8.4 % OM; high coliforms	Arable	A little untidy; professional installation, filter clean	System installed 2 years ago; Filter changed every 6 months by owner/professional. Bulb not changed.	Low pH, colour, TOC, low-moderate turbidity, generally low metals except substantial Fe spike Q2.	Low pH (Q2). High Fe & Al (Q4).UV transmittance high (81-96 %).
31	Fe and Mn filters; UV disinfection; pH correction	Well	Sandy silt loam; 9.5 % OM; low coliforms	Grazing	Owner installation; Filter brown	System installed 2 years ago. Professionally serviced once to fix pump; owners change filters and UV bulbs every 5 years.	High colour, neutral pH, very high TOC, turbidity, Al and Fe. Low Mn. UV transmittance very low-low (19-44 %).	Low pH throughout, high turbidity and Al Q1 and high Fe Q1 & 3.UV transmittance high-very high (86-98 %).

Site ID	Water Treatment Description	Type of Supply	Soil Characteristics	Catchment Type	Appearance of Treatment system on first visit	System age and maintenance	Source water quality	Tap water quality issues
32	20 µm filter; 5 µm filter; UV disinfection; softener balls	Well	Sandy silt loam; 12.2 % OM; high coliforms	Grazing	Professional installation, filters may be slightly brown	System installed 3 years ago. Unclear whether professional servicing. Owner changes lamp, filters and softener balls annually.	Generally low colour, TOC, turbidity (can be elevated – Q2), low pH, generally low metals but can be elevated (Mn Q1; Al, Fe Q2). UV transmittance generally fairly high (84-88 %) can be low (59 % Q2).	High Mn (Q1). High colour, TOC & Al (Q2).

Fourteen sites incurred potable water microbiological failures once or more during the quarterly sampling campaign. These sites are detailed in Table 3.13 above. The sites included spring supplies (1), surface supplies (3-4; site 4 changed from surface to borehole after Q1), well supplies (7) and boreholes (2). Of the fourteen sites, ten were situated in sub-catchments used for some form of livestock grazing. Three had tree cover (woodland or forestry) nearby and two had arable land as a significant land use within the direct sub-catchment of the supply. The prevalent soil types were sandy loam and sandy silt loam and most had a high to very high organic content. The coliform loading of the soils ranged from very low to high, with a fairly even spread across the ten sites for which data were able to be gathered. Ten of the treatment systems were installed 2-3 years ago, 2 were installed (or had UV installed) around 6-7 years ago and two systems were installed 13-15 years ago. Seven installations were carried out by professional installers, four by plumbers and three were by owners/unknown installers. On the first visit to the sites, filters were visibly brown at six out of seven sites where the filters could be seen through a transparent casing. Twelve of the fourteen sites had some form of filtration prior to UV. One had no additional treatment and for one site (9) it was unclear whether the water conditioner included any form of filter. Four sites were characterised as having standard filtration and UV treatment only, while the remainder had more complex treatment systems including carbon filters, sand filters, sediment tanks, pH correction and chlorination. The treatment at seven of the sites included fine filtration (5-10 µm) filters. Three sites had element (Fe/Mn) removal treatments. Treatment systems at two sites did not undergo any form of servicing, one of which had been installed only two years ago (site 18), but the other had been installed over six years ago (site 23) with no form of maintenance. At the remaining twelve sites, ten of the systems were maintained annually or more frequently while two only received attention every 2-3 years and every 5 years respectively, although the latter system was only two years old therefore had only been without maintenance for this period at the time of the first sampling. (It appears that the owner's intention was to service every 5 years). With regard to maintenance, there was an equal split between those maintained solely by owners, solely by professionals and with a mixture of the two. Tap water chemical quality issues were dominated by elevated colour, TOC and metals (primarily Fe and Mn) which reflected high source water loadings.

Specific findings for individual sites are detailed below:

Site 1 had one minor microbiological fail in Q2 which coincided with a chemical fail for Mn. Chemical fails for Fe, Mn and colour occurred at Q1,3 and 4 without associated microbiological fails, despite associated low UV transmittance readings. Interestingly, the microbiological fail occurred when the UV transmittance of the tap water was high (91 %) yet there was no microbiological fail when the UV transmittance dropped to 34 % (Q4), associated with high TOC, Fe and Mn. The Fe scavenger as part of the

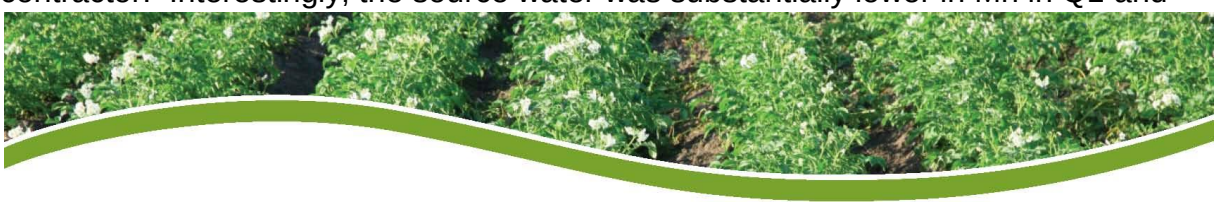
treatment system appears to be insufficient to deal with the high Fe loading of the source water.

Site 3 had three microbiological fails (Q1,3 and 4), despite a chlorination programme in addition to the UV disinfection. In this case, the only microbiological pass occurred when the UV transmittance for this site was at its highest (68% at the tap). The treatment system (coarse and fine filtration) has a minimal, if any effect on the UV transmittance from source to tap. There is also a concern that a system with high organic loading and poor removal prior to chlorination is likely to be generating disinfection by products.

Site 4 incurred a microbiological fail only during Q1 when this site was a surface supply. This corresponded with a chemical fail for Fe and an associated very low UV transmittance of 25% at the tap. The owners installed a borehole and subsequent samples passed both microbiological and chemical standards despite the borehole source water having elevated levels of Mn substantially greater than the original surface water. The three-filter treatment system (25 µm; 10 µm; carbon filter) appeared to be removing Mn sufficiently during the study.

Site 8 potable water incurred microbiological fails during Q1 and Q2. The site always failed for colour and failed twice (Q1 and 4) for Fe and typically had poor UV transmittance at the tap. One of the microbiological fails corresponded with a chemical fail (Q1) but the second occurred when the tap water had the highest UV transmittance for the site (albeit still poor for tap water at 66%). At this site, the owner was particularly engaged with his water supply and thought he had an effective schedule for maintaining his filters, based on visible fouling of the coarse filter. Following the installation of a settling tank, the visible fouling became less apparent, but the quartz sleeve of the lamp was becoming fouled. It appears that particulates were removed in the settling tank and fouling became related to dissolved or fine particulate material. This demonstrates that positive changes in treatment can be associated with water quality changes that change visual cues to maintain the system. The owner increased the frequency (to ~ 3 monthly) of cleaning of the filters and tap water passed microbiological standards in Q3 and 4. This was not sufficient to eliminate the significant colour problems associated with this surface supply.

Site 9 potable water failed microbiological standards during Q3 and Q4 but failed throughout Q1-4 due to elevated Mn. UV transmittance remained fairly high (89 %) when microbiological fails occurred. The UV transmittance recorded at the tap during Q1 at 20 % seems unlikely, given the range of the other parameters measured at source and tap and appears indicative of laboratory data inputting error (91.8 instead of 19.8). Data are shown as received in reports from the accredited laboratory contractor. Interestingly, the source water was substantially lower in Mn in Q1 and



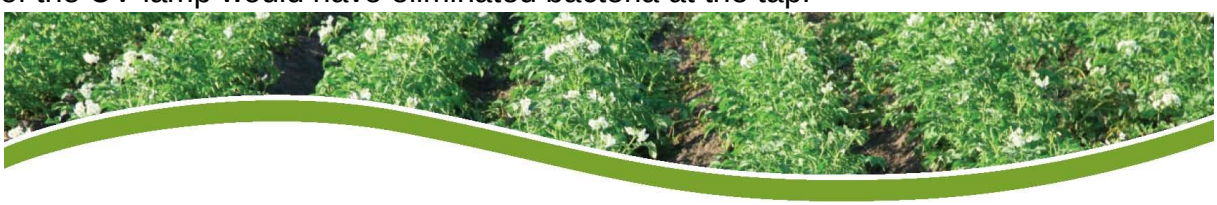
Q2, indicating either a substantial lag time from source to tap (which seems unlikely for a well supply) or that filters become saturated during prior source Mn spikes, subsequently becoming a source of Mn leaching into tap water.

Site 10 failed microbiological parameters during Q3 and failed chemical parameters throughout with respect to elevated Mn and also for elevated Fe in Q3. Hence, the microbiological fail occurred when both Mn and Fe were high, despite there being no evidence of a change in UV transmittance at tap (which was fairly high throughout at 80-82 %) or source. As for Site 9, fails for elevated Mn occurred at the tap even when source water Mn loading was lower, suggesting an effect of prior events.

Site 14 had two microbiological fails (Q3 and Q4) but passed chemical quality standards throughout. There is no clear reason for the fail from the data, given that source water quality, including microbiological quality, was particularly good at this sampling time. This site was selected for monthly monitoring based on the high water quality during Q1, and no chemical fails were detected throughout the monthly sampling. One further microbiological failure occurred prior to Q2.

Site 18, burn supply in upland moorland, failed throughout the quarterly sampling for microbiological parameters. This site was also selected for monthly sampling as an example of a site with severe water quality issues and filters and UV were replaced during March 2014. Microbiological fails occurred at all but one of the monthly sampling events. In contrast to many sites, microbiological fails at site 18 were frequently due to low numbers of *Clostridium perfringens*, with coliform and *E. coli* presence becoming more frequent from June onwards. Clostridia can be indicative of less recent pollution events, thus the effect of bypassing the storage tank on the system was evaluated during one sampling occasion and this had no significant impact on results. Clostridia are prevalent throughout the environment therefore can be expected within a surface water supply. What is perhaps surprising is the relatively low numbers of *E. coli* and coliforms detected at the tap. The appearance of fails related to *E. coli*/coliforms appeared to correspond with increasing source and tap concentrations of Fe from June onwards. Interestingly, source Mn was low throughout the majority of the monthly sampling, peaking only during the final sampling in September 2014. The storage tank would have generated a lag between source at tap but it is surprising that so few source samples corresponded with spikes in Mn at the tap. In this case, leaching from filters is less likely to account for this as filter replacement had no clear effect on concentrations of Mn at the tap.

Site 23 failed microbiological standards during Q3. The site had no chemical fails throughout with the exception of low pH and there was no change in chemical water quality when the microbiological fail occurred. However, the UV treatment system was aged (6 years +) and had not been serviced, thus it is likely that regular replacement of the UV lamp would have eliminated bacteria at the tap.



Site 26 failed microbiological standards in Q1 and failed for chemistry (elevated Al, Fe and turbidity) in Q2. Again, in Q2, the potable sample had a higher concentration of Fe and Al than the source, demonstrating the importance of prior water quality events.

Site 28 incurred microbiological fails during Q2 and 4 but did not fail for chemistry during the quarterly sampling programme. There were notable source water spikes of Fe and Al during Q3, thus these elements may play a role in fouling of the system over time and reducing UV efficacy. UV transmittance of the tap water samples remained high throughout.

Site 30 failed microbiological parameters in Q1 and had elevated Fe and Al in potable samples (fails) in Q4. Again, there was no direct correspondence of the microbiological fail with chemistry spikes, although there was a small increase in turbidity in Q1 compared with the other sampling occasions. There was no corresponding source spike when the potable sample failed for high Fe and Al, as described for other sites above.

Site 31 failed microbiological parameters during Q1, corresponding with chemistry fails for turbidity, Al and Fe and a decrease in UV transmittance to 86 %. The site also failed for chemistry (high Fe) in Q3 with no associated microbiological fail. Source Fe and Al were consistently very high throughout, thus the treatment system (which includes element filters) has a significant effect on the water quality but cannot completely remove large spikes of Fe. It also appears that the pH correction is surplus to requirements as the source water is neutral and actually leads to chemical fails for low pH.

Site 32 underwent a microbiological fail during Q2 when the UV transmittance decreased substantially (to 59 %). The corresponded with a chemical fail for colour and Al. A chemical fail for Mn occurred in Q1. Site 32 was selected for monthly monitoring a site which the owner maintained very carefully with generally good quality based on Q1 data. There was one further microbiological fail throughout the monthly sampling and no further chemical fails.

Sites failing microbiological parameters can be broadly characterised as follows:

- Installations carried out by either professionals, plumbers or owners
- Filtration of some sort – coarse, fine or both is installed prior to UV disinfection
- Filters are maintained and bulbs are replaced at least annually for most sites
- Maintenance may be carried out by owners or professionals
- Dominance of grazing/upland catchments
- Range of soil loading of coliforms
- Soils tend to be high in OM

- Sources waters are tend to be high in metals, TOC and colour
- UV transmittance may be low, high or variable.
- Potable water tends to fail once or more for high concentrations of metals and colour.
- Microbiological fails do not necessarily correspond directly with chemistry fails
- Indication that past water quality events are important – spikes of poor source water quality may influence subsequent potable water chemical and microbiological quality potentially through leaching from saturated filters or fouling of UV lamp surfaces.

More frequent sampling is likely to identify water quality issues arising for a particular source therefore it is useful to review whether, in the context of monthly sampling data, quarterly samples sufficiently identify the key water quality issues for a given supply.

Site 14
Quarterly sampling: 2 microbiological fails; no chemical fails
Monthly sampling: 3 microbiological fails; no chemical fails

Site 17
Quarterly sampling: No microbiological fails; no chemical fails
Monthly sampling: 1 microbiological fail; 2 chemical fails (pH)

Site 18
Quarterly sampling: 4 microbiological fails; 2 chemical fails (colour, Fe, Mn)
Monthly sampling: 11 microbiological fail; 8 chemical fails (colour, Fe, Mn, pH)

Site 19
Quarterly sampling: No microbiological fails; 4 chemical fails (colour, turbidity, Fe, Mn, pH)
Monthly sampling: 1 microbiological fail; 12 chemical fails (colour, turbidity, Fe, Mn, pH)

Site 32
Quarterly sampling: 1 microbiological fails; 2 chemical fails (colour, Al, Mn, pH)
Monthly sampling: 2 microbiological fail; 2 chemical fails (colour, Al, Mn, pH)

Site 37
Quarterly sampling: No microbiological fails; 2 chemical fails (pH)
Monthly sampling: No microbiological fail; 4 chemical fails (pH)

All water quality issues identified during monthly sampling of the above supplies were also identified during quarterly sampling, with the exception of pH fails at sites 17 and 18. Microbiological fails during quarterly sampling appeared broadly representative of the microbial quality of the water. This indicates that quarterly sampling should be sufficient to gain a reasonable appraisal of water quality at a given site for the purposes of determining whether treatment systems are adequate. However, the variation in water quality across quarterly sampling data indicates that sampling less frequently or one-off sampling is unlikely to be representative of water quality issues at a given site and when designing treatment systems, other factors such as catchment type and soil characteristics should be considered if one-off sampling of water quality is the only option.

General analysis and trends

In tap waters, there was very little difference between TOC and filtered TOC, indicating the majority of organic carbon reaching the tap was in dissolved form (DOC). Within the quarterly sample data, TOC ranged from 0.2-12.4 mg l^{-1}, with 83% of the samples under 4 mg l^{-1}. Turbidity ranged from 0.1-11.4 NTU, with 95% of the samples meeting the regulatory standard of 4 NTU. The five occasions where quarterly samples arose with high turbidity were across all four quarters and across four different sites within Aberdeenshire. They were not associated with higher TOC or manganese, but were associated with high iron and usually with high aluminium and the same samples tended to yield higher colony counts at 37 ºC but were only associated in one case with bacterial fails (*C. perfringens*, rather than coliforms/*E. coli* which tends to be indicative of less recent contamination).

Microbiological fails occurred across all four quarters and across all regions. Of those samples which failed microbiological standards, 58% also had high levels of Aluminium, Iron or Manganese (above the regulatory standard for one or more of these metals). Of the samples which passed microbiological standards, only 20 % also failed for one of iron, aluminium or manganese.

Quarterly data

Analysis of counts (colony forming units, CFU) of bacteria in source waters compared to tap waters showed that the treatment systems present did reduce numbers of bacteria, but were not 100% effective at removing bacteria. While there were no significant differences noted between the sampling quarters, there was a trend towards larger numbers of bacteria present in both source and tap waters during Quarter 4. This was especially notable for *E. coli* and coliforms (see Figure 3.2 - Figure 3.5)

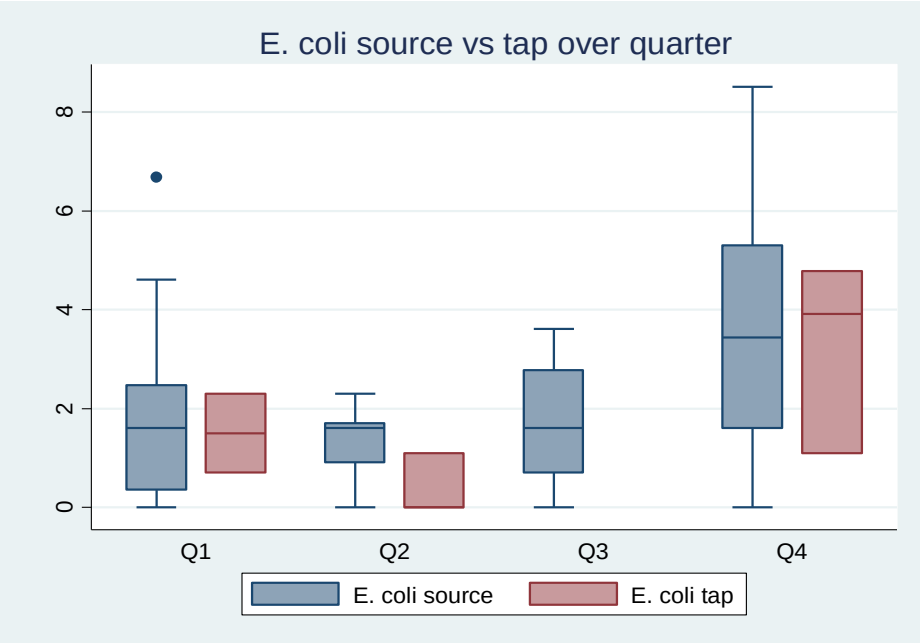


Figure 3.2 *E. coli* (cfu ml^{-1}) in source waters vs. tap waters over the four sampling quarters (Q1 – Q4)

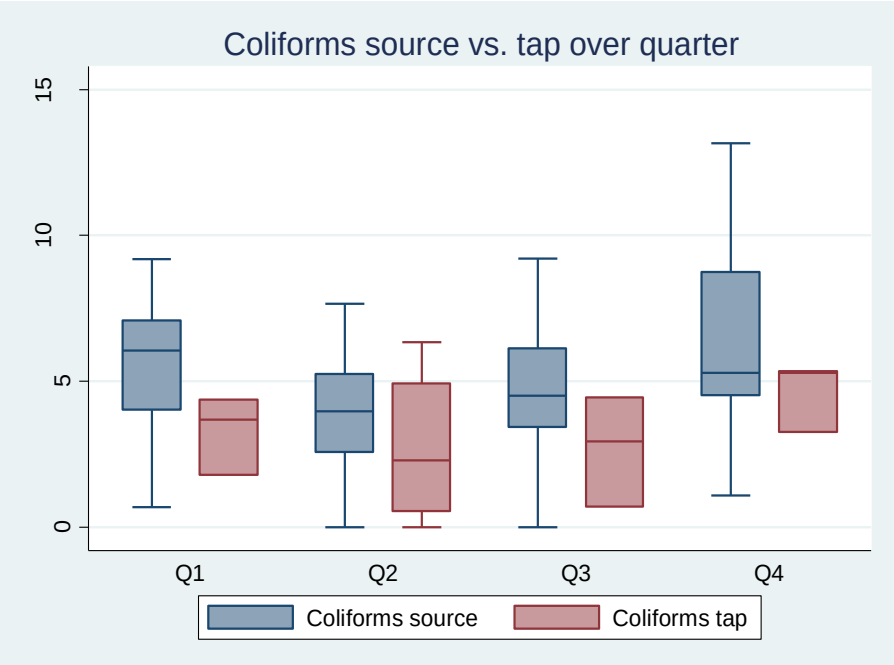


Figure 3.3 Coliforms (cfu ml^{-1}) in source waters vs. tap waters over the four sampling quarters (Q1 – Q4)

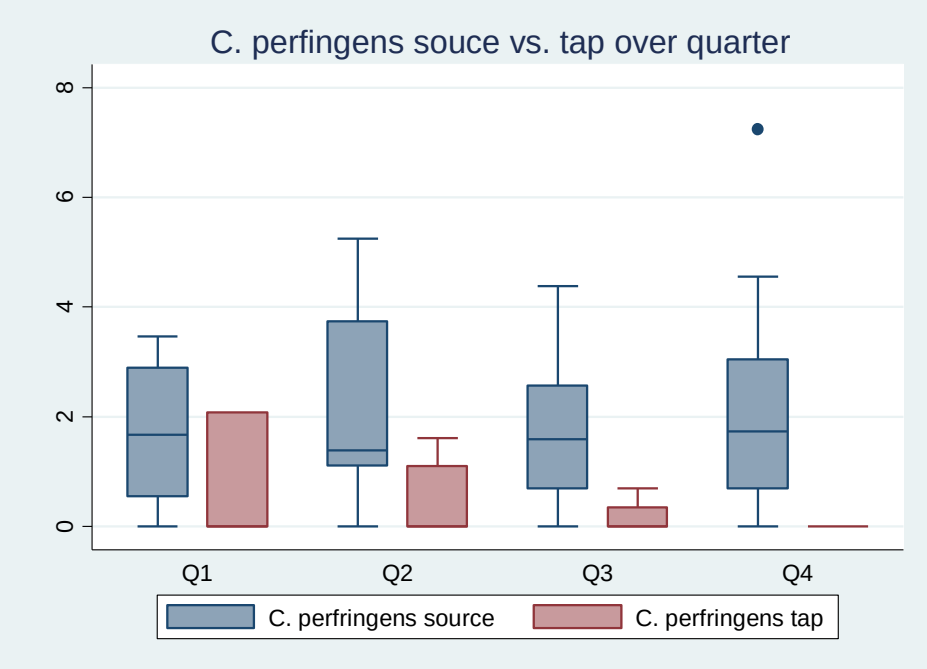


Figure 3.4 *C. perfringens* (cfu ml^{-1}) in source waters vs. tap waters over the four sampling quarters (Q1 – Q4)

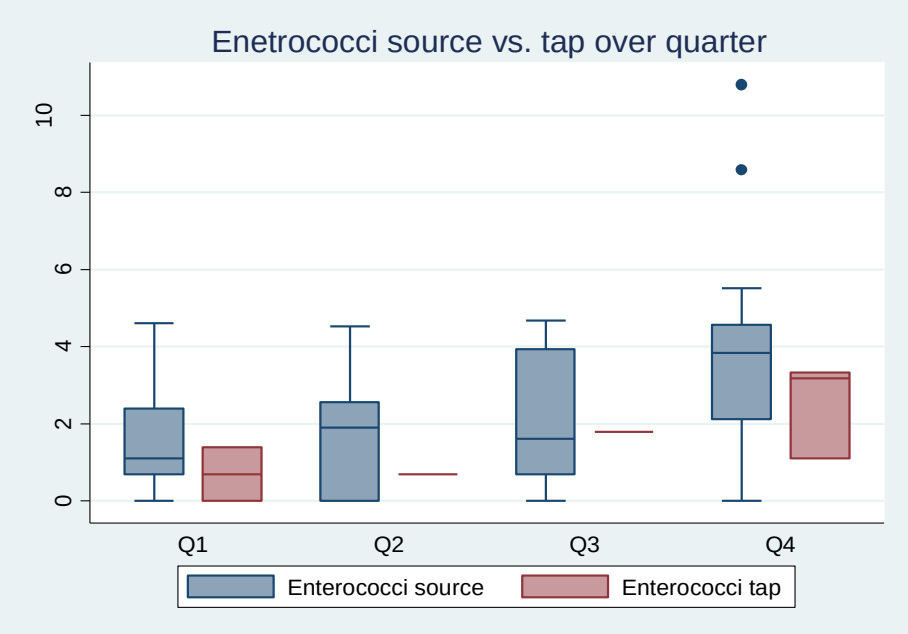


Figure 3.5 Enterococci (cfu ml^{-1}) in source waters vs. tap waters over the four sampling quarters (Q1 – Q4)

Each PWS water source was categorized into four catchment typologies based on dominant land-use within the catchment; namely “arable”, “grazing (intensive)”, “grazing (extensive) and “forestry”. A similar analysis was performed to the above, with numbers of bacteria (cfu ml^{-1}) in source vs. tap waters assessed for each catchment typology. Again, in all cases bacterial loading reduced as a result of the treatment systems installed. Interestingly (although possibly not unexpected), bacterial numbers present in tap water were only significant for the two grazing land uses, with largest tap water bacterial loadings associated with extensive grazing. This pattern is seen for all bacterial parameters (see Figure 3.6 - Figure 3.9). Clearly, animals are a source of bacteria and animals are far more likely to be in close proximity to water sources in catchments dominated by grazing systems. The more extensive grazing systems are less likely to fence animals within specific areas of land and there is also likely to be more wildlife. This may result in more regular access of animals to areas in close proximity to water sources and may explain why tap water failure is more likely for supplies located in these catchment typologies.

A similar analysis was performed to investigate bacterial numbers present in source and tap waters by supply type (borehole, rainwater, spring, surface supply and well). Significant bacterial numbers (cfu ml^{-1}) of all types measured were found in tap waters from surface and well supplies. Significant numbers (cfu ml^{-1}) of *C perfingens* were also found in tap water from spring supplies (see Figure 3.10 - Figure 3.13)

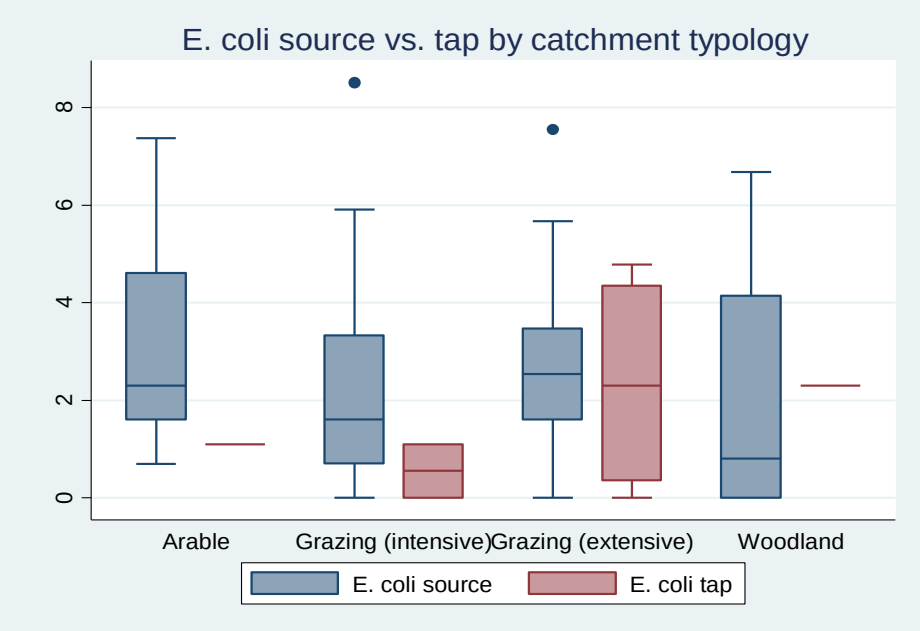


Figure 3.6 *E. coli* (cfu ml^{-1}) in source vs. tap waters from supplies located in different catchment typologies (catchments dominated by (i) arable land, (ii) intensive grazing, (iii) extensive grazing, (iv) forestry).

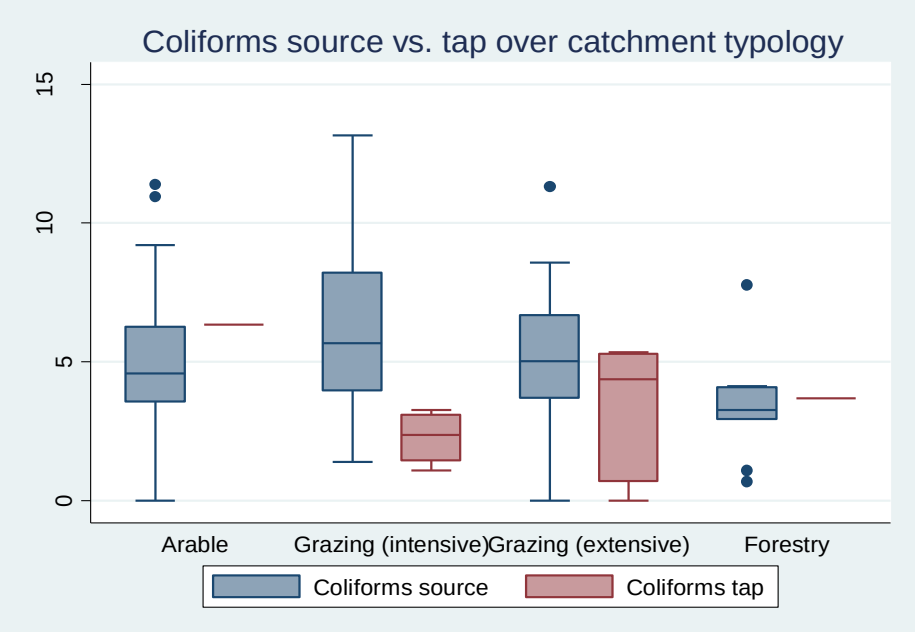


Figure 3.7 Coliforms (cfu ml^{-1}) in source vs. tap waters from supplies located in different catchment typologies (catchments dominated by (i) arable land, (ii) intensive grazing, (iii) extensive grazing, (iv) forestry).

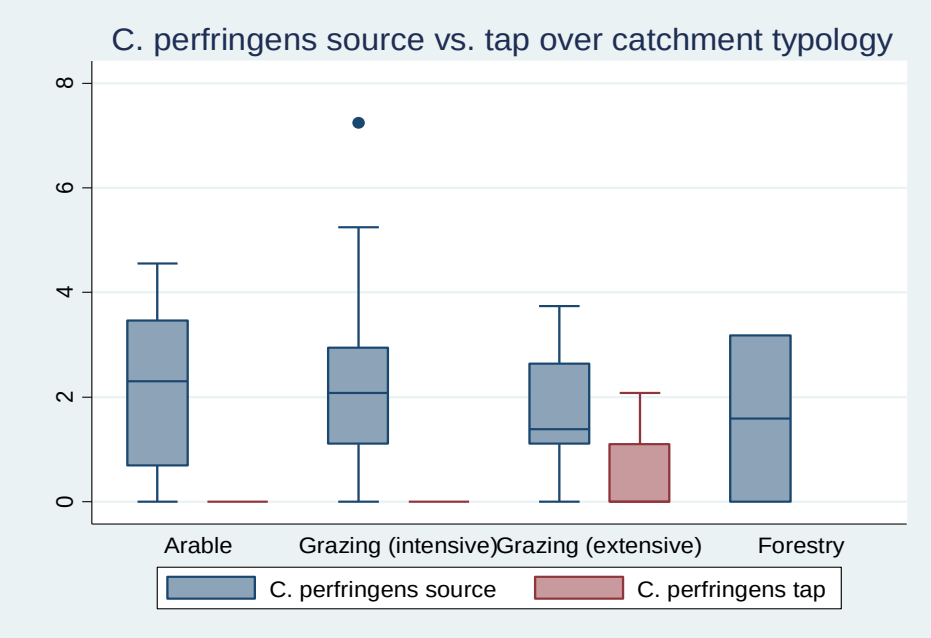


Figure 3.8 *C. perfringens* (cfu ml^{-1}) in source vs. tap waters from supplies located in different catchment typologies (catchments dominated by (i) arable land, (ii) intensive grazing, (iii) extensive grazing, (iv) forestry).

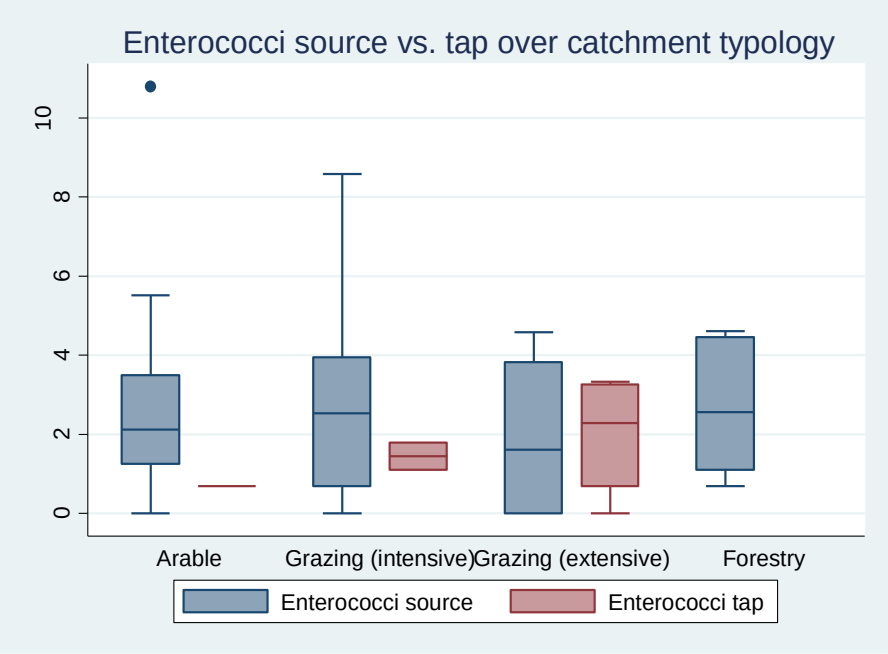


Figure 3.9 Enterococci (cfu ml^{-1}) in source vs. tap waters from supplies located in different catchment typologies (catchments dominated by (i) arable land, (ii) intensive grazing, (iii) extensive grazing, (iv) forestry).

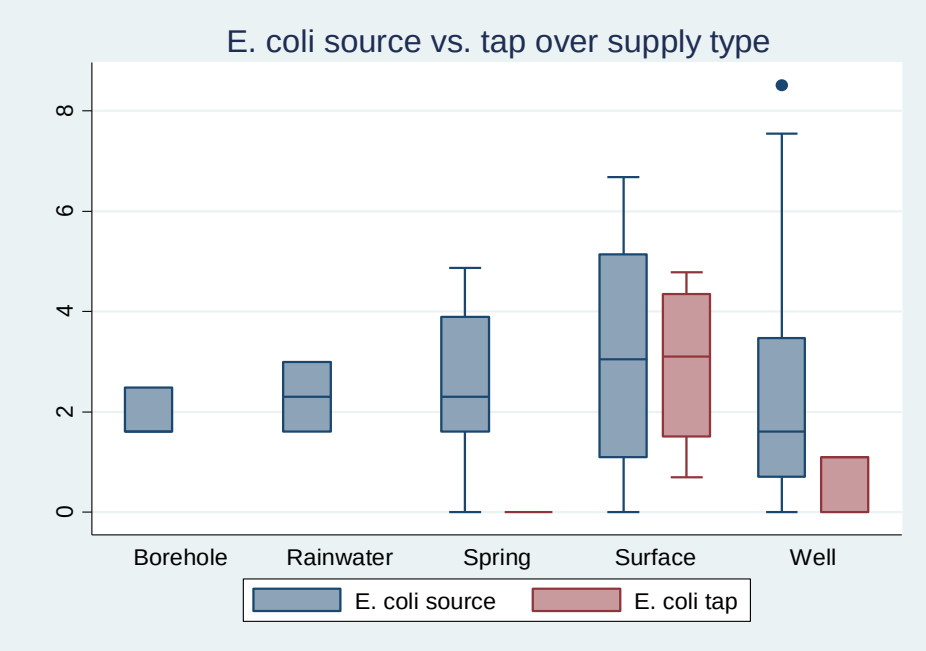


Figure 3.10 *E. coli* (cfu ml^{-1}) in source vs. tap waters for different supply types covered by this study.

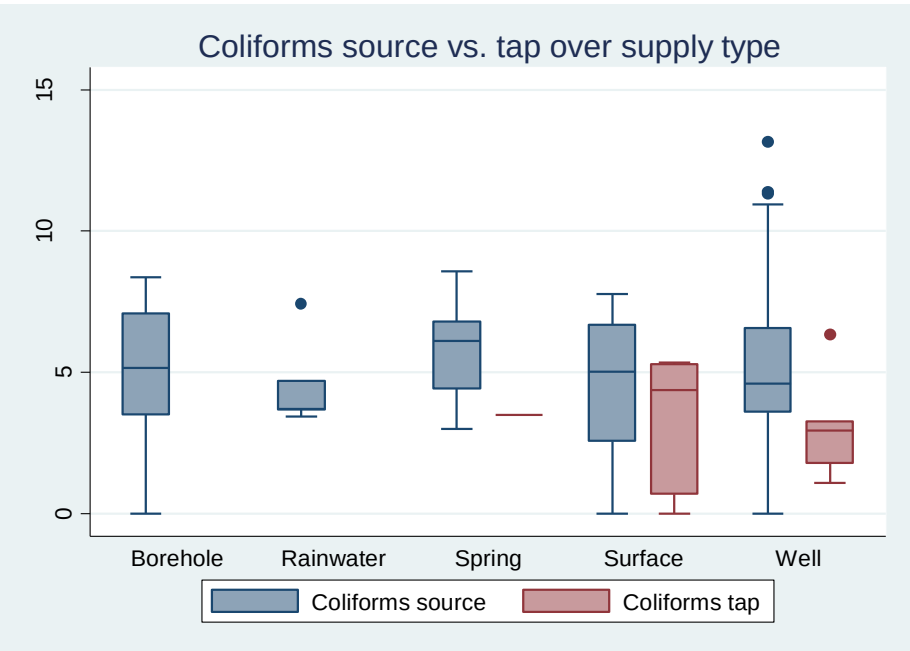


Figure 3.11 Coliforms (cfu ml^{-1}) in source vs. tap waters for different supply types covered by this study.

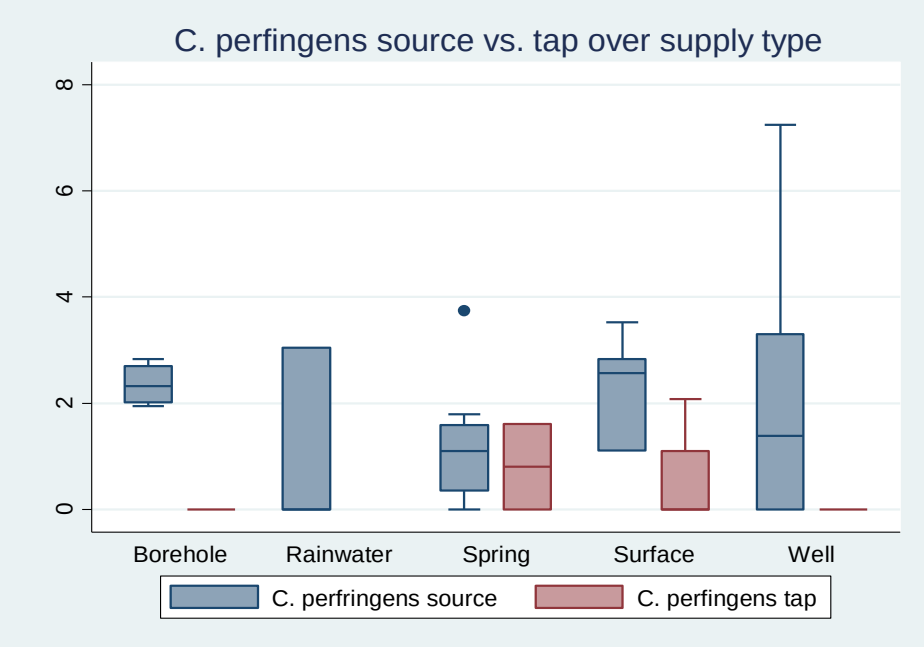


Figure 3.12 *C. perfringens* (cfu ml^{-1}) in source vs. tap waters for different supply types covered by this study.

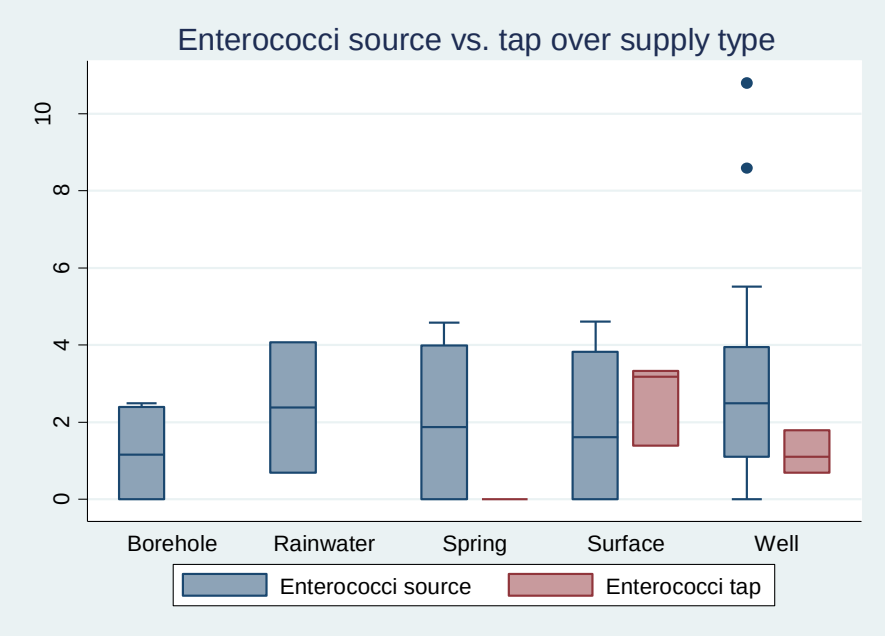


Figure 3.13 Enterococci (cfu ml^{-1}) in source vs. tap waters for different supply types covered by this study.

The next series of graphs (Figure 3.14 - Figure 3.25) all show bacterial counts (cfu ml^{-1}) in source and tap waters as a function of various physic-chemical parameters (UV transmittance, turbidity, TOC) known to be important in effectiveness of UV for disinfection. In each case, the physico-chemical parameter has been divided into four quartiles. For UV transmittance (Figure 3.14 - Figure 3.17), there is a clear pattern with concentrations of bacteria (cfu ml^{-1}) in tap water being closely related to source waters that have low UV transmittance (<86 %). This is the case for all four bacterial indicators. A similar (but opposing) trend is seen with turbidity (NTU; Figure 3.18 - Figure 3.21), with concentrations of bacteria being mainly associated with more turbid source waters. However, this trend is not as clear cut as for UV transmittance and in a number of cases, waters as low as 0.2 NTU were measured as having significant concentrations of Coliforms and Enterococci. Again, similar trends can be seen with TOC (Figure 3.22 - Figure 3.25).

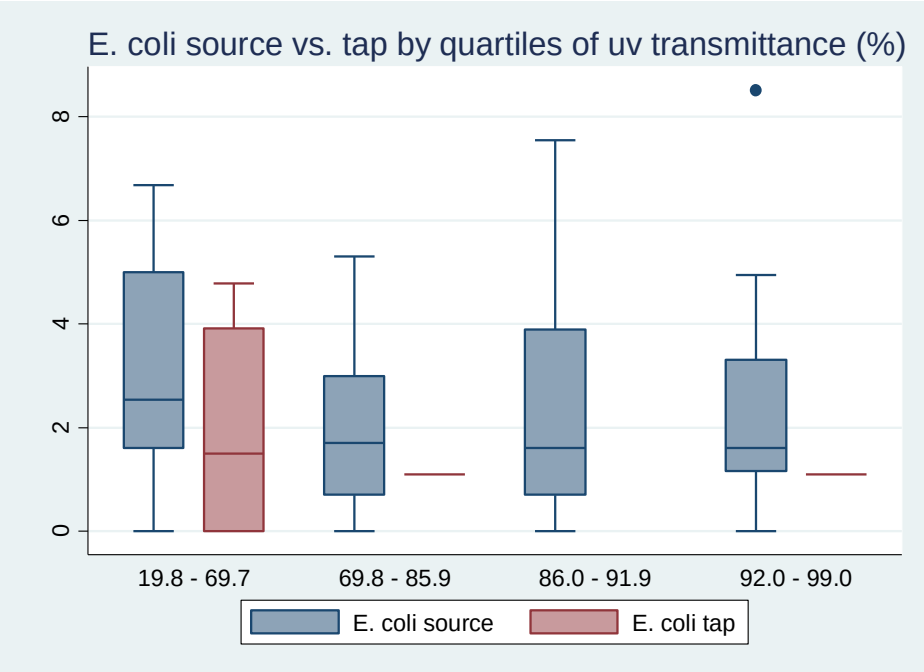


Figure 3.14 *E. coli* (cfu ml^{-1}) in source vs. tap waters for different quartiles of UV-transmittance (%)

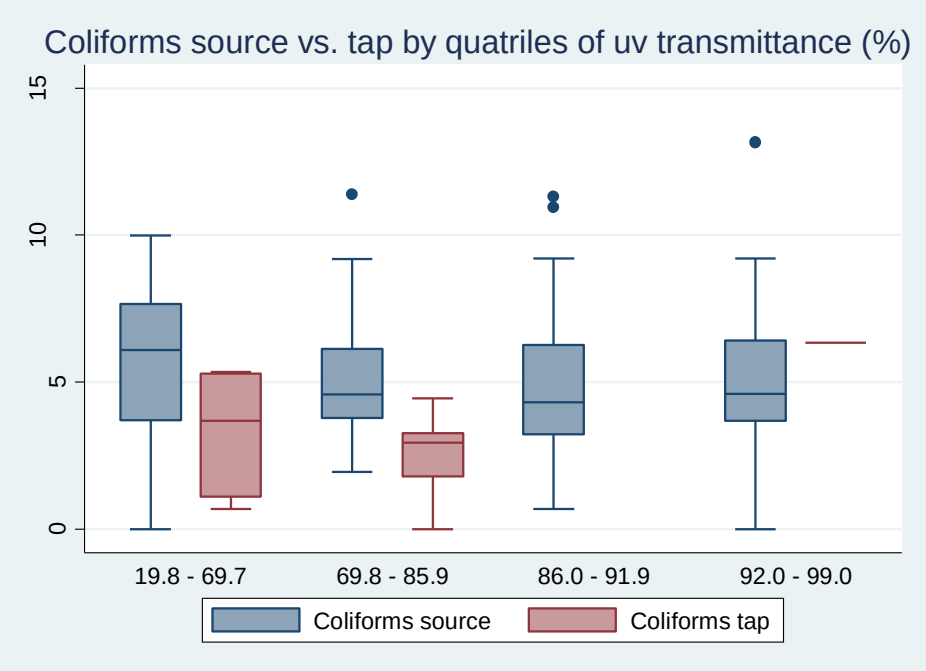


Figure 3.15 Coliforms (cfu ml^{-1}) in source vs. tap waters for different quartiles of UV-transmittance (%)

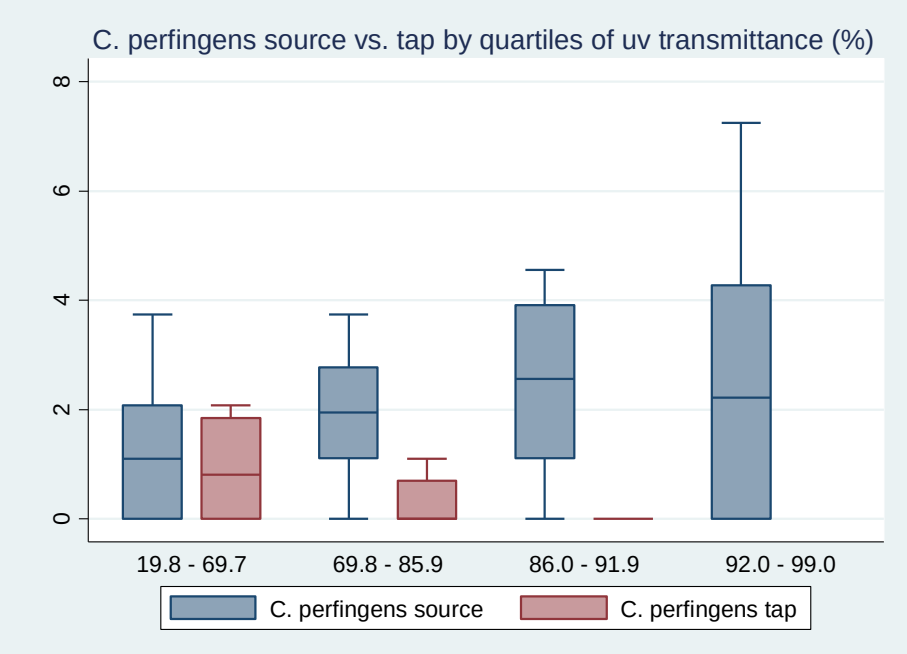


Figure 3.16 *C. perfringens* (cfu ml^{-1}) in source vs. tap waters for different quartiles of UV-transmittance (%)

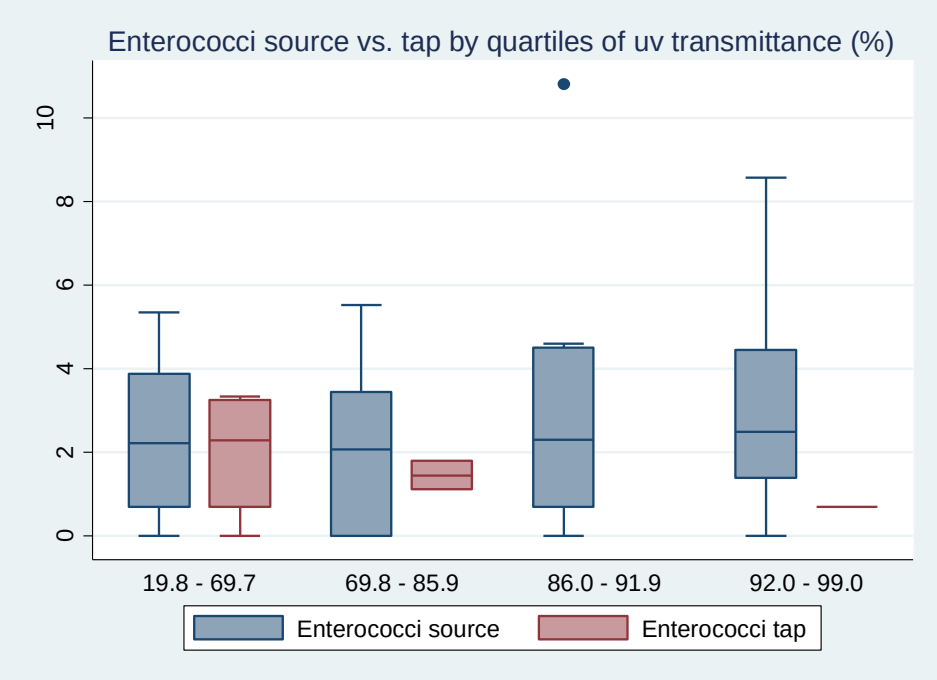


Figure 3.17 Enterococci (cfu ml^{-1}) in source vs. tap waters for different quartiles of UV-transmittance (%)

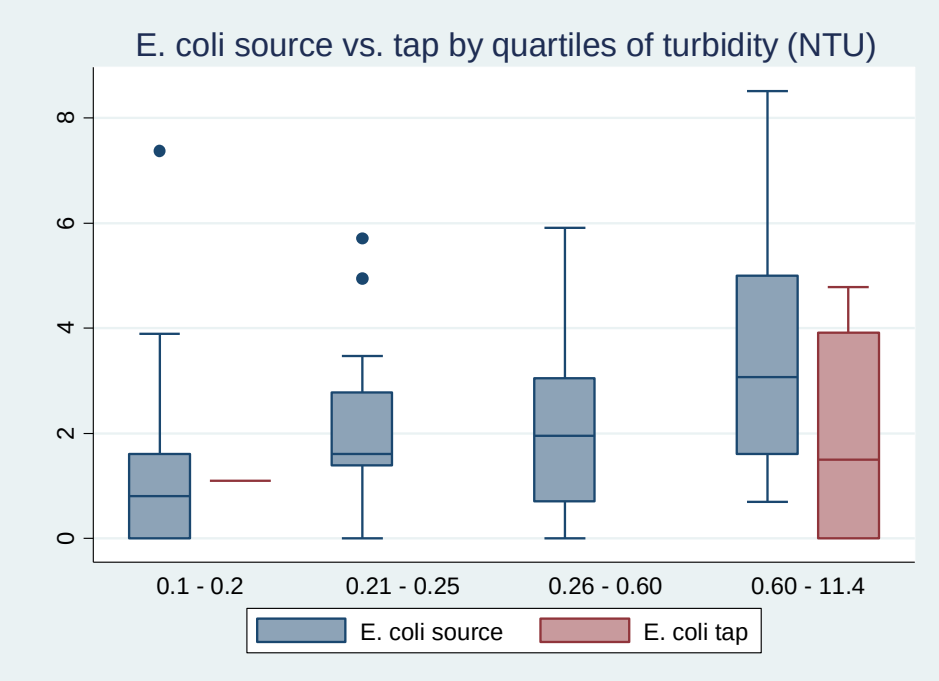


Figure 3.18 *E. coli* (cfu ml^{-1}) in source vs. tap waters for different quartiles of turbidity (NTU)

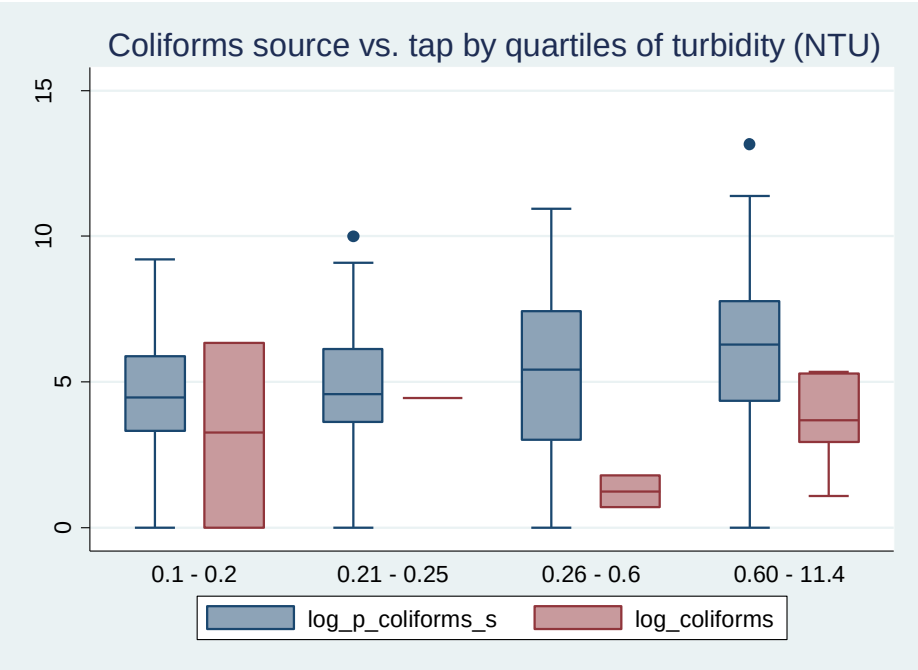


Figure 3.19 Coliforms (cfu ml^{-1}) in source vs. tap waters for different quartiles of turbidity (NTU)

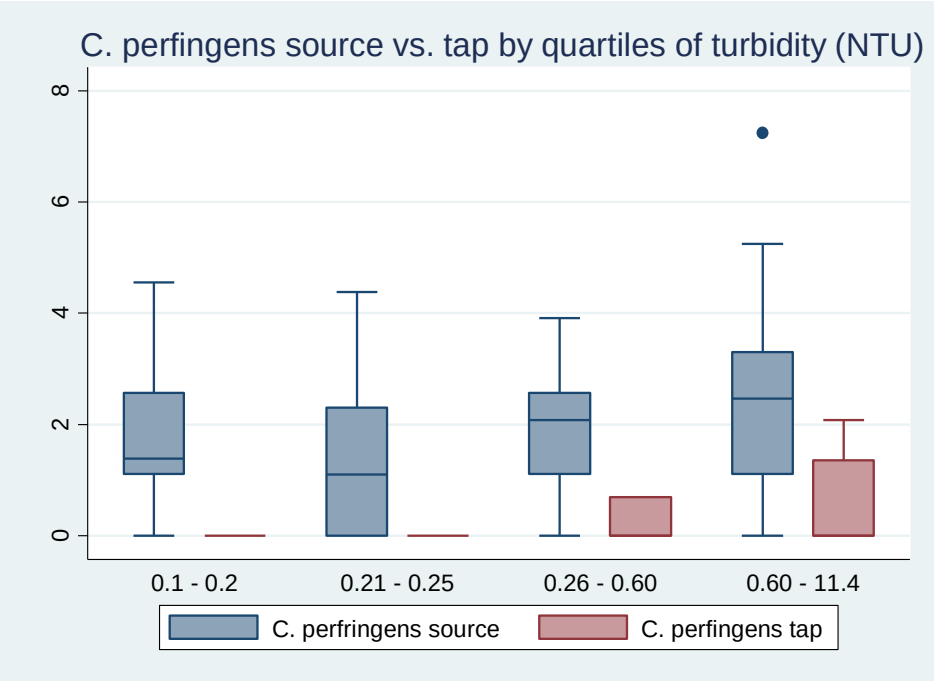


Figure 3.20 *C. perfringens* (cfu ml^{-1}) in source vs. tap waters for different quartiles of turbidity (NTU)

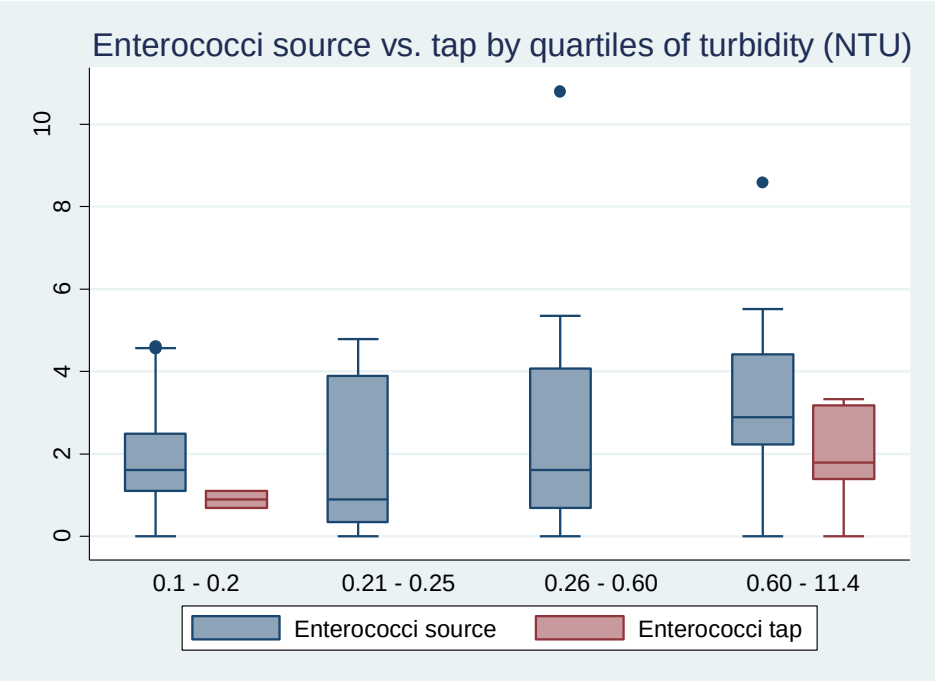


Figure 3.21 Enterococci (cfu ml^{-1}) in source vs. tap waters for different quartiles of turbidity (NTU)

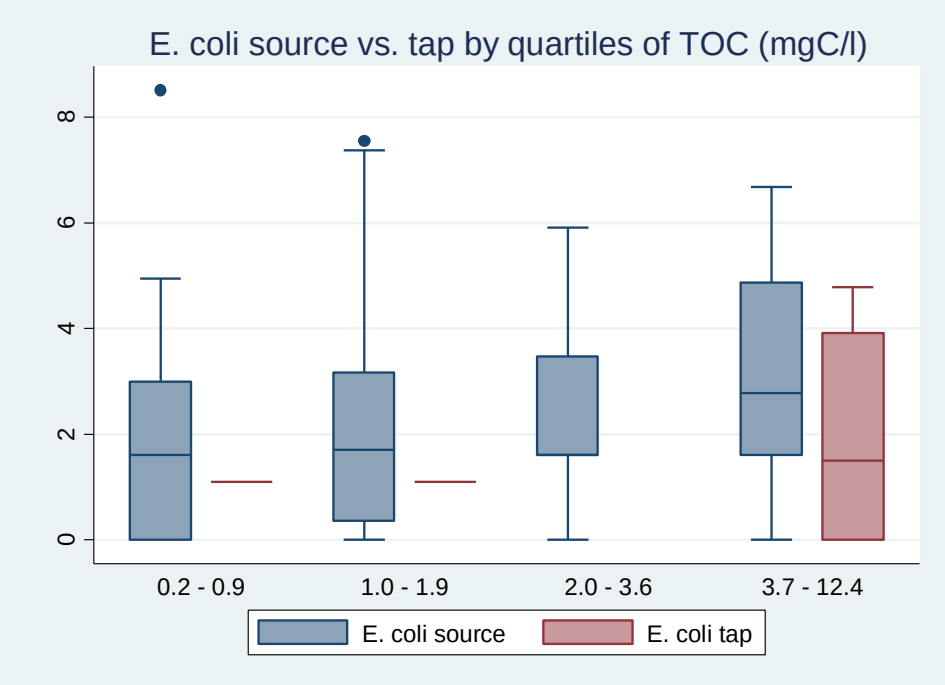


Figure 3.22 *E. coli* (cfu ml^{-1}) in source vs. tap waters for different quartiles of TOC (mg C l^{-1})

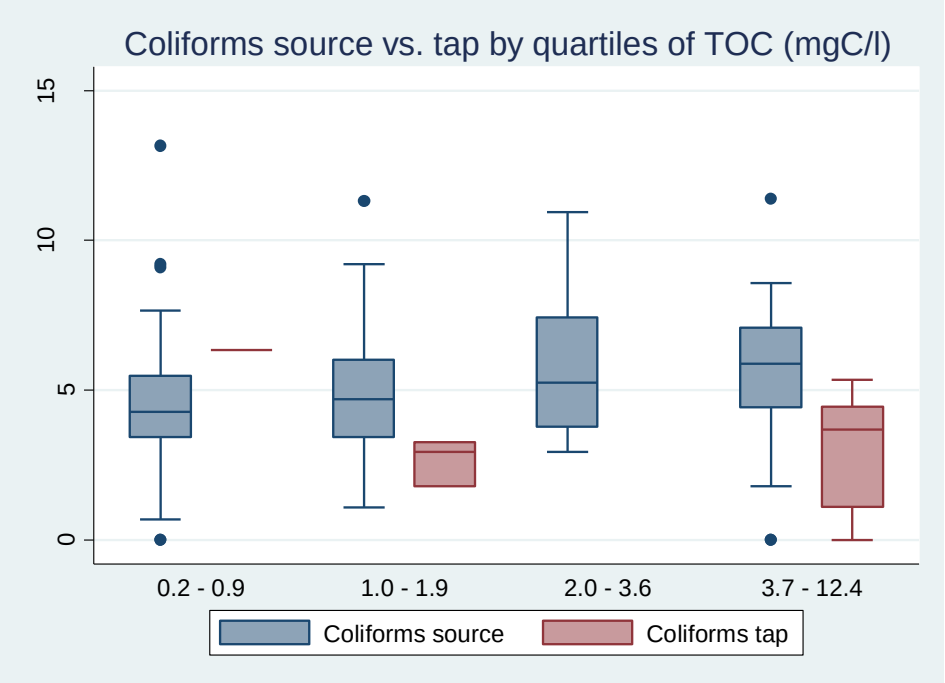


Figure 3.23 Coliforms (cfu ml^{-1}) in source vs. tap waters for different quartiles of TOC (mg C l^{-1})

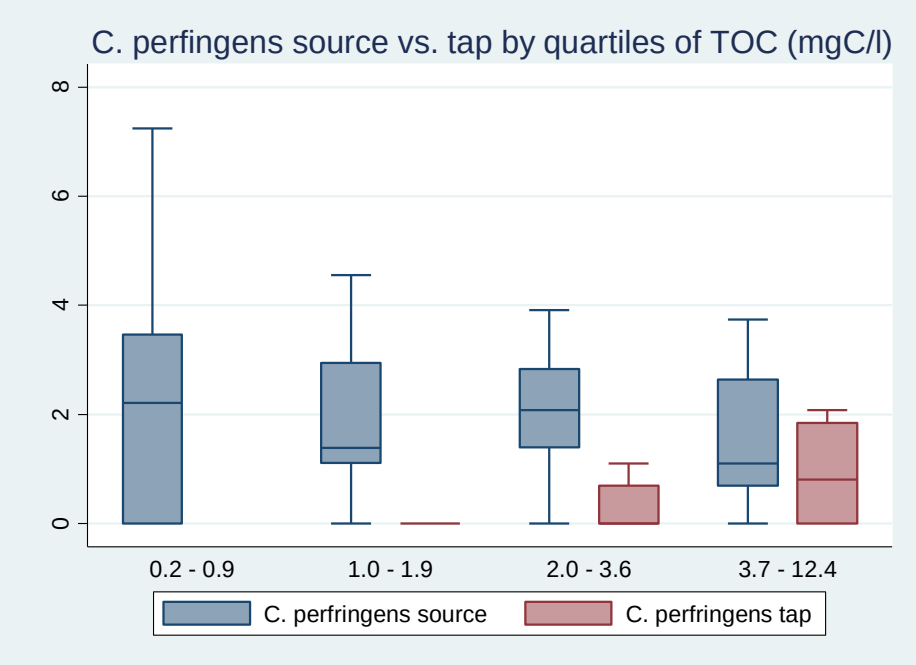


Figure 3.24 *C. perfringens* (cfu ml^{-1}) in source vs. tap waters for different quartiles of TOC (mg C l^{-1})

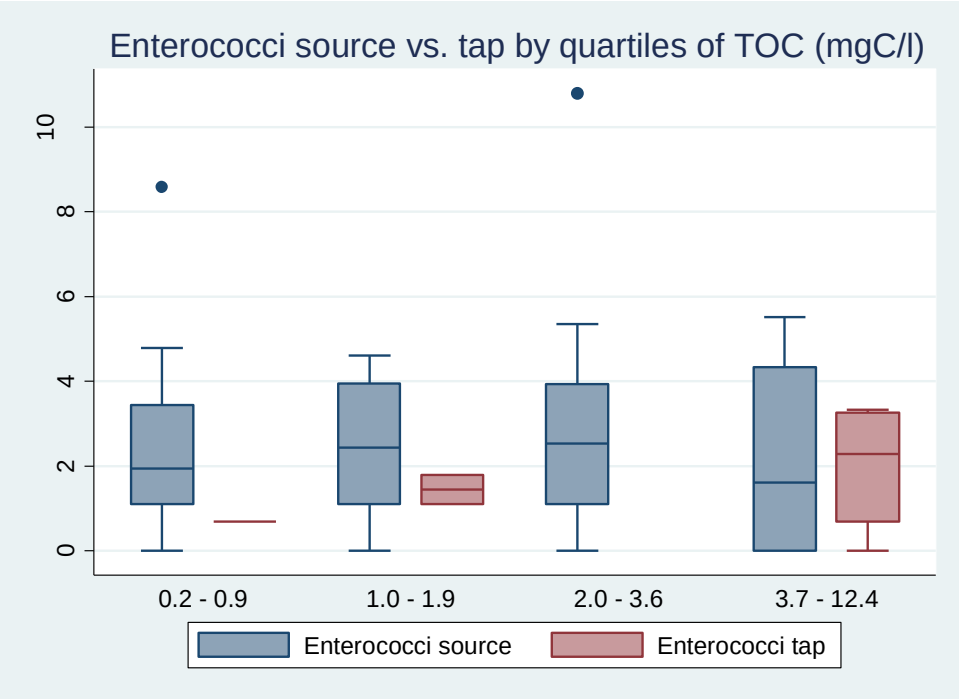


Figure 3.25 Enterococci (cfu ml^{-1}) in source vs. tap waters for different quartiles of TOC (mg C l^{-1})

Looking at catchment typology and supply types, UV transmittance tends to be lowest in waters sourced from catchments dominated by grazing systems, especially where grazing is extensive (Figure 3.26). Unsurprisingly, UV transmittance also tends to be lowest in surface and spring supplies as these source waters are likely to be most influenced by surface/environmental conditions (Figure 3.27). Very similar trends, although not as pronounced, were seen for TOC (Figure 3.28 & Figure 3.29); and to a much lesser extent for turbidity (Figure 3.30 & Figure 3.31). No trends were evident for the main chemical elements (Al, Fe, Mn) either by catchment typology or by supply type (Figure 3.32 & Figure 3.33).

These findings further support the theories that surface-influenced supplies situated in catchments dominated by grazing systems pose greatest risk to water quality.

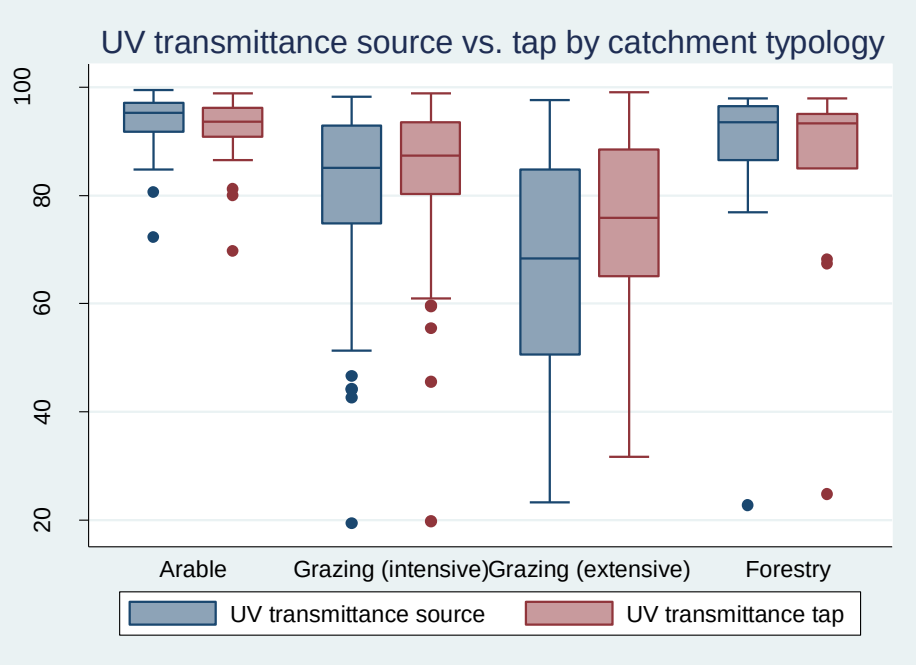


Figure 3.26 UV transmittance (%) in source and tap waters from water supplies located in different catchment typologies

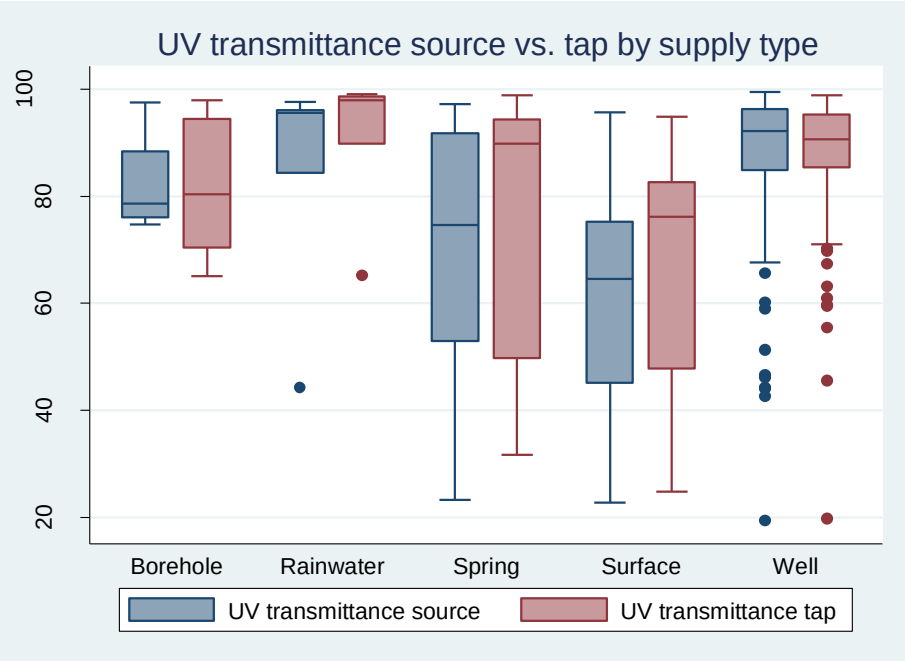


Figure 3.27 UV transmittance (%) in source and tap waters from different types of water supply

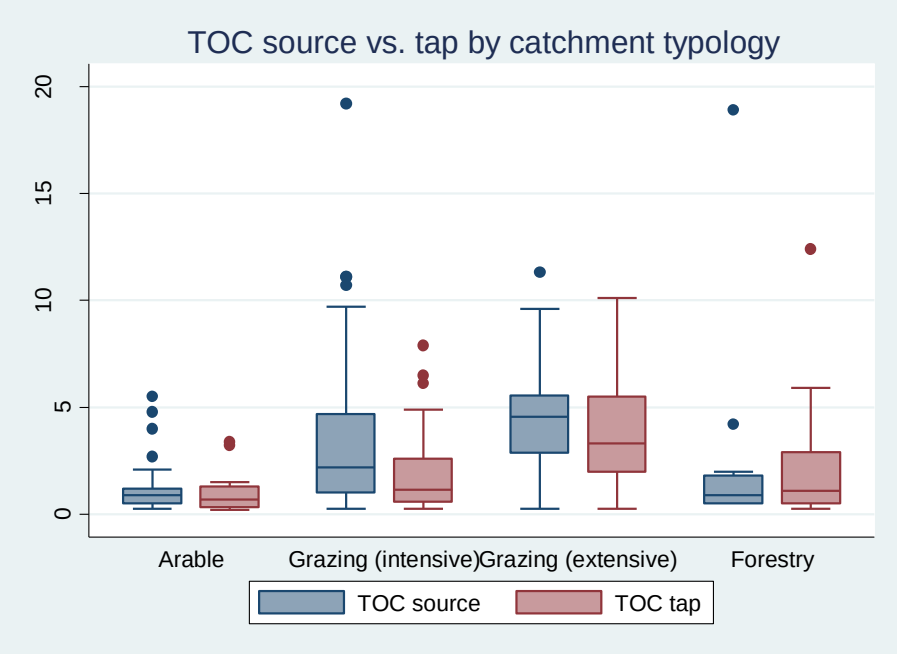


Figure 3.28 TOC (mg C l^{-1}) in source and tap waters from water supplies located in different catchment typologies

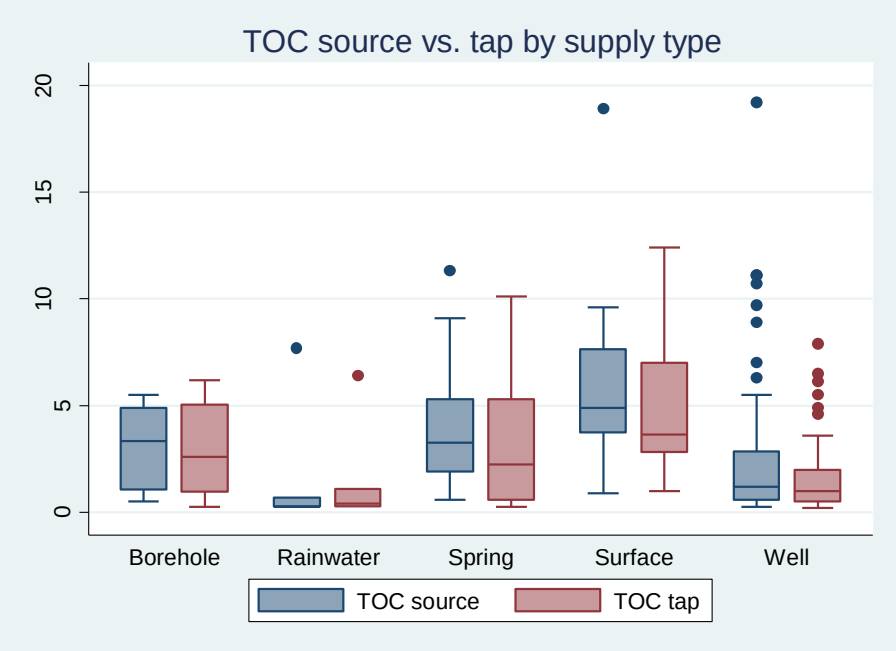


Figure 3.29 TOC (mg C l^{-1}) in source and tap waters from different types of water supply

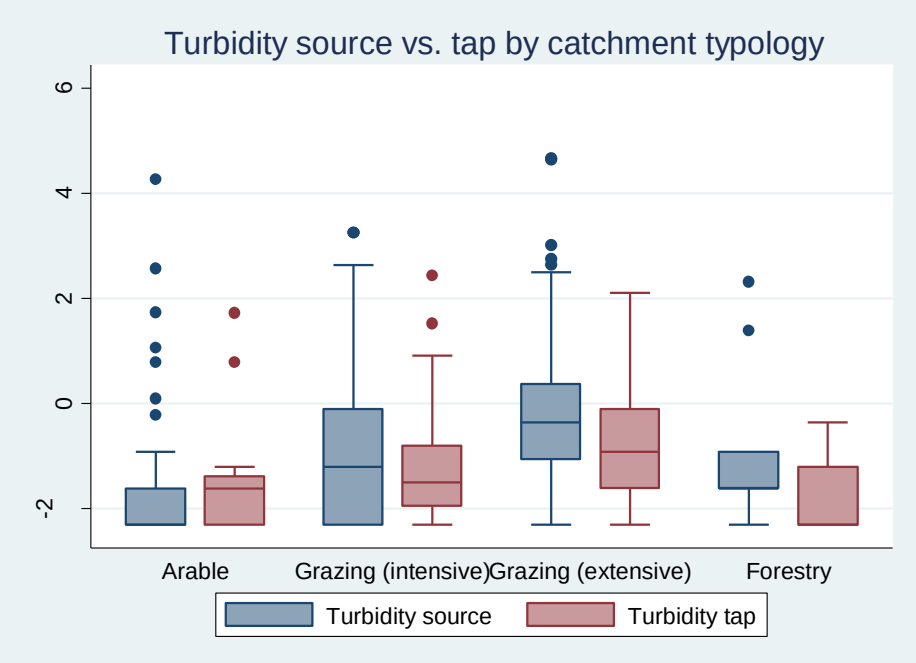


Figure 3.30 Turbidity (NTU) in source and tap waters from water supplies located in different catchment typologies

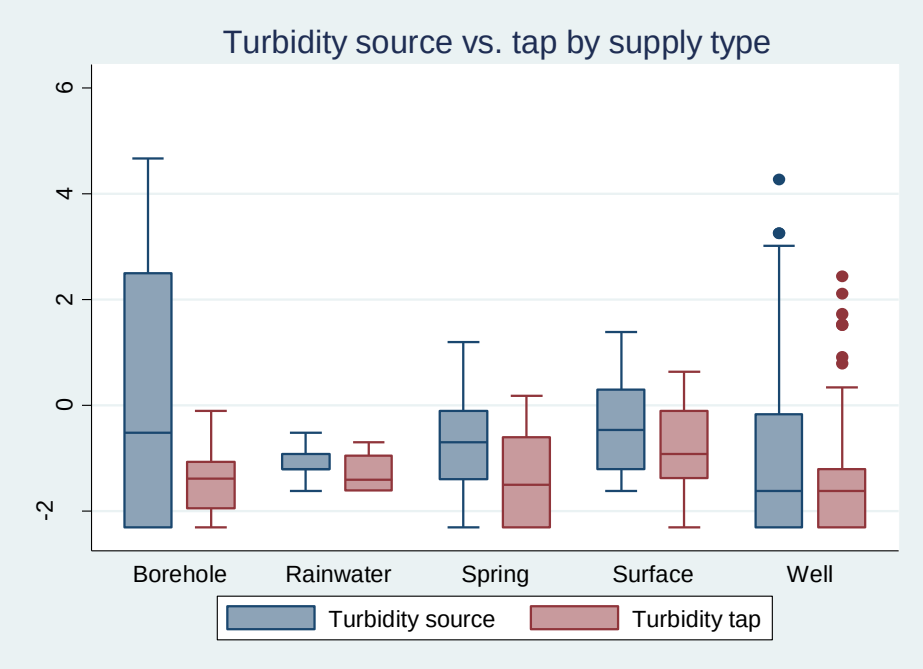


Figure 3.31 Turbidity (NTU) in source and tap waters from different types of water supply

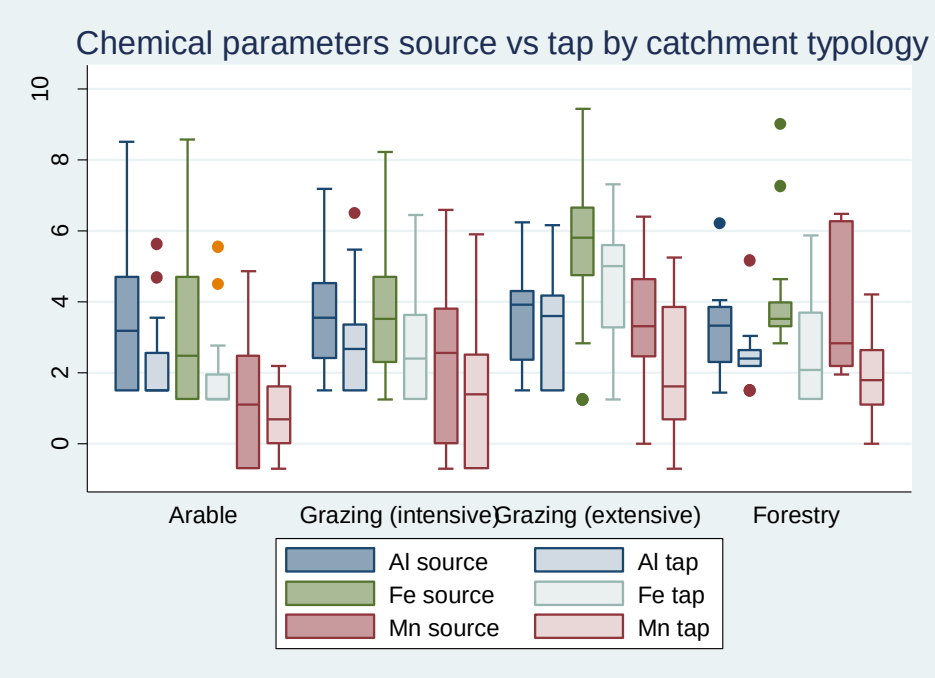


Figure 3.32 Chemical parameters (Al, Fe, Mn; mg l^{-1}) in source and tap waters from water supplies located in different catchment typologies

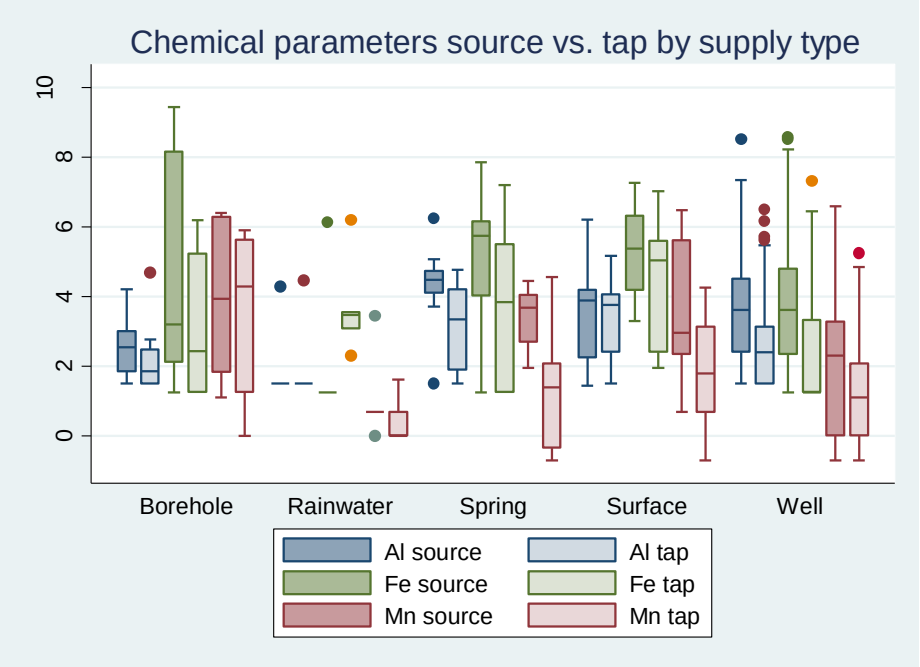


Figure 3.33 Chemical parameters (Al, Fe, Mn; mg l^{-1}) in source and tap waters from different types of water supply

Monthly data

The monthly data were used to track within-site variation and temporal changes in bacterial loading in source vs. tap waters to investigate whether changes to source water quality had a subsequent effect on tap water compliance. This was investigated on a site by site basis (Figure 3.35 - Figure 3.46). The relationship with rainfall (Figure 3.34) was also evaluated. As described in the methodology, the majority of monthly sampling sites were selected because they appeared on initial inspection to be well maintained systems. The only exception was ID 18 that had specific treatment challenges. This was a surface supply that was so heavily coloured that any form of filtration used simply clogged resulting in pump burn-out. As a result the owner had removed all forms of filtration and only a UV treatment bulb was present. The results from ID 18 therefore provide some indication of the effectiveness of the UV treatment system in the absence of pre-filtration. For the majority of the monthly sampling sites, the treatment systems performed very effectively with the majority of tap samples identified as having zero bacterial loads despite large variability in source water quality (2 – 8 log cfu bacteria ml^{-1}). The only obvious exception was ID 18 (Figure 3.39 & Figure 3.40) where bacteria of between 4 – 6 log cfu ml^{-1} were still present post-treatment.

The monthly data were also used to statistically assess whether recent rainfall was having an effect on top of the effect of log(source TOC) which had been identified for

the quarterly data. No significant effect was found. One of the sites failed on all occasions and one site never failed, but it should be noted that there was considerable temporal variability with two sites failing once, one site failing twice and one site failing three times. These failures are likely to have been missed if only annual or quarterly samples were taken.

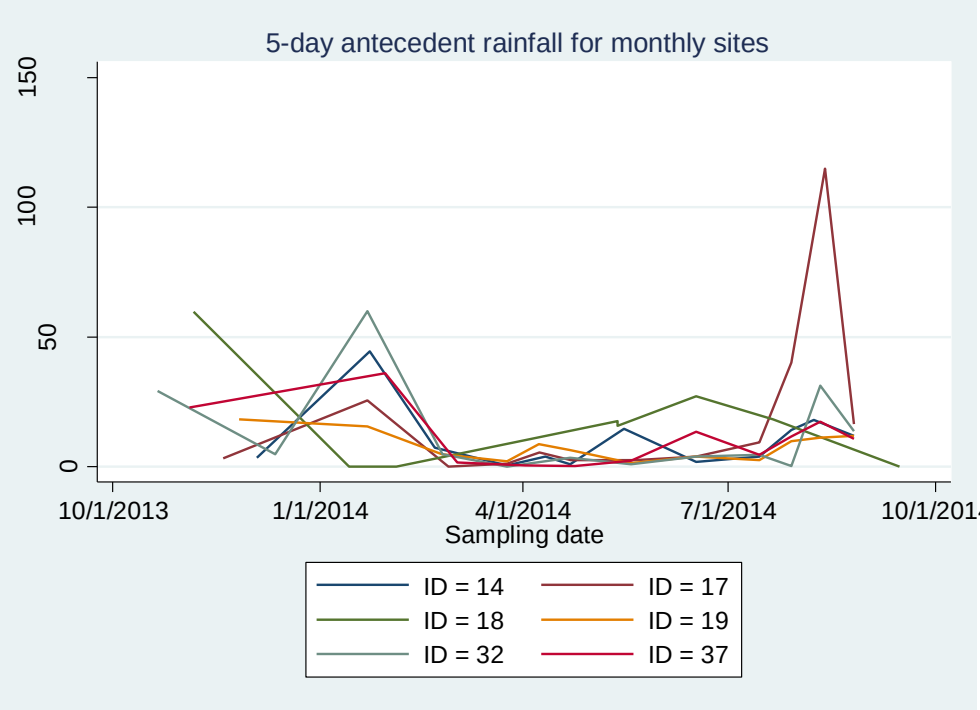


Figure 3.34 5-day antecedent rainfall for monthly sites

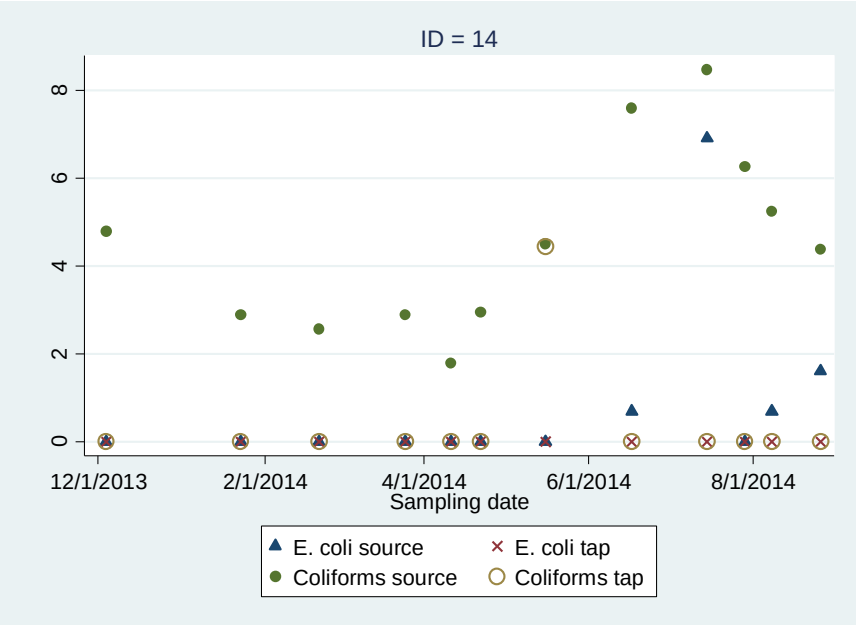


Figure 3.35 *E. coli* and coliforms (log cfu ml^{-1}) in source and tap waters from sampling site 14, over time

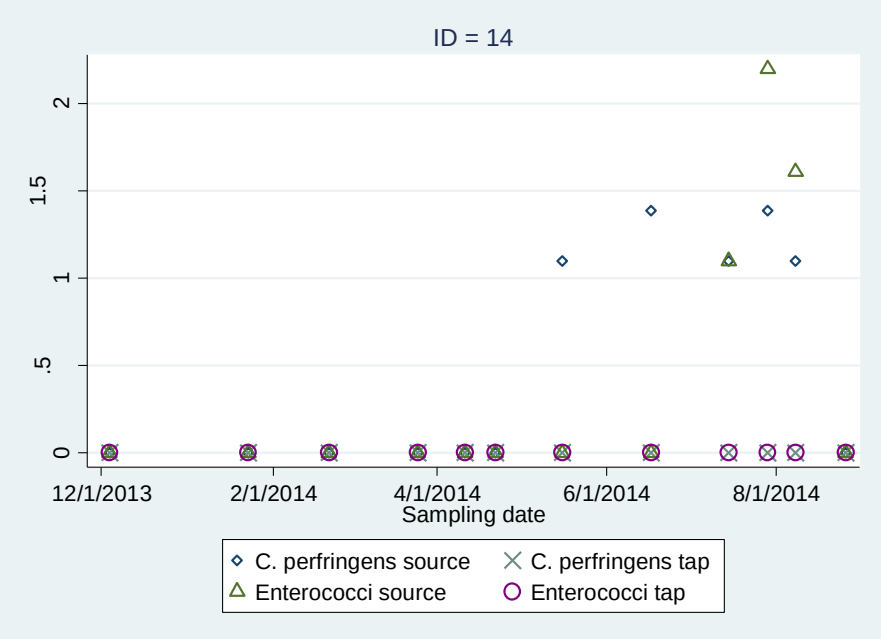


Figure 3.36 *C. perfringens* and enterococci (log cfu ml^{-1}) in source and tap waters from sampling site 14, over time

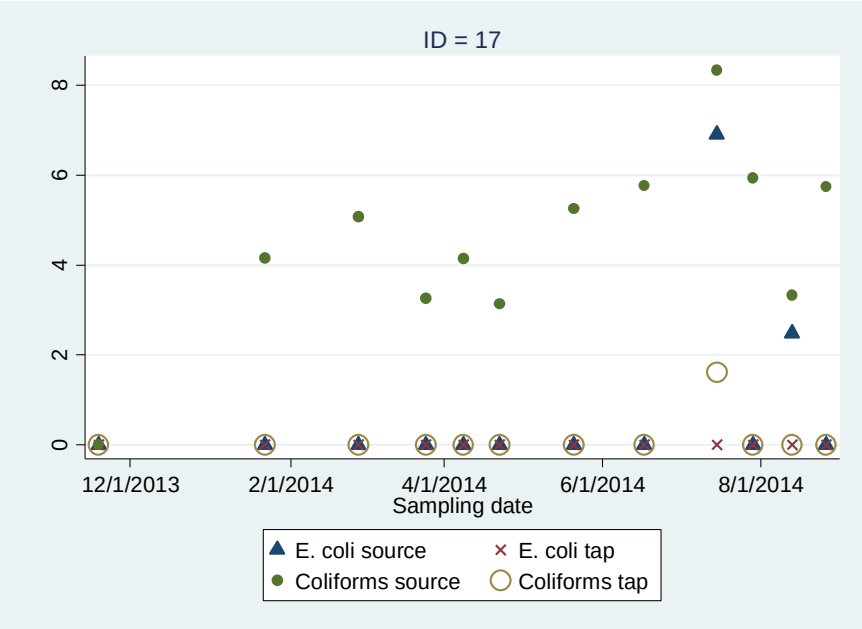


Figure 3.37 *E. coli* and coliforms (log cfu ml^{-1}) in source and tap waters from sampling site 17, over time

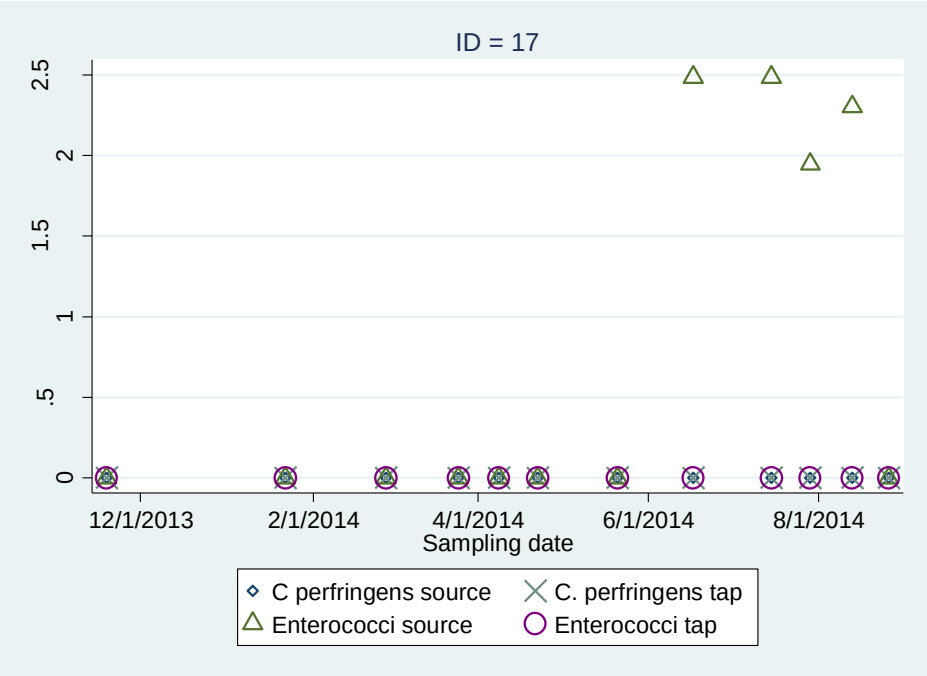


Figure 3.38 *C. perfringens* and enterococci (log cfu ml^{-1}) in source and tap waters from sampling site 17, over time

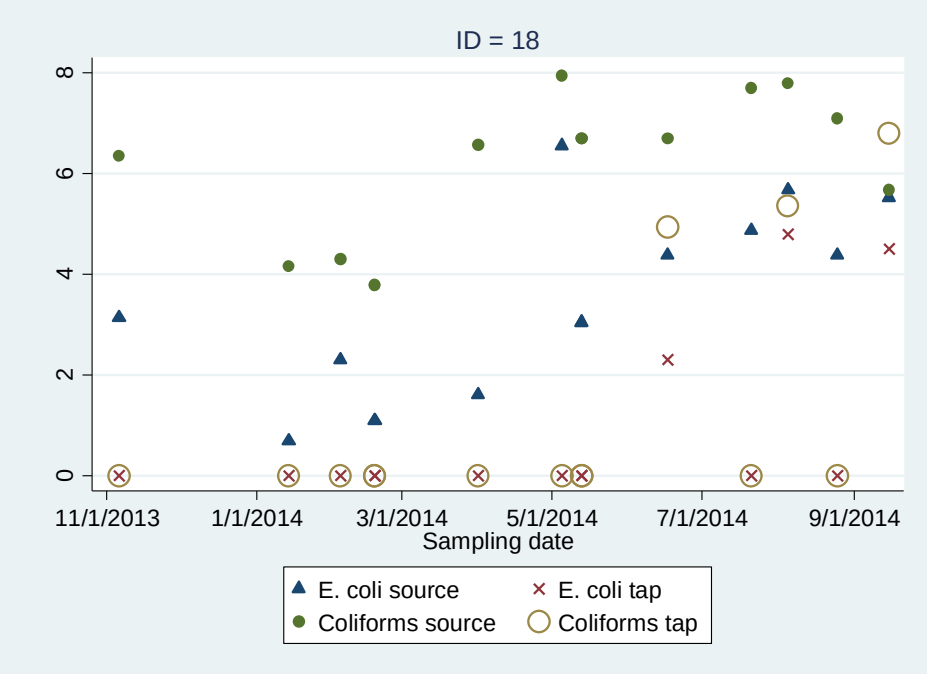


Figure 3.39 *E. coli* and coliforms (log cfu ml^{-1}) in source and tap waters from sampling site 18, over time

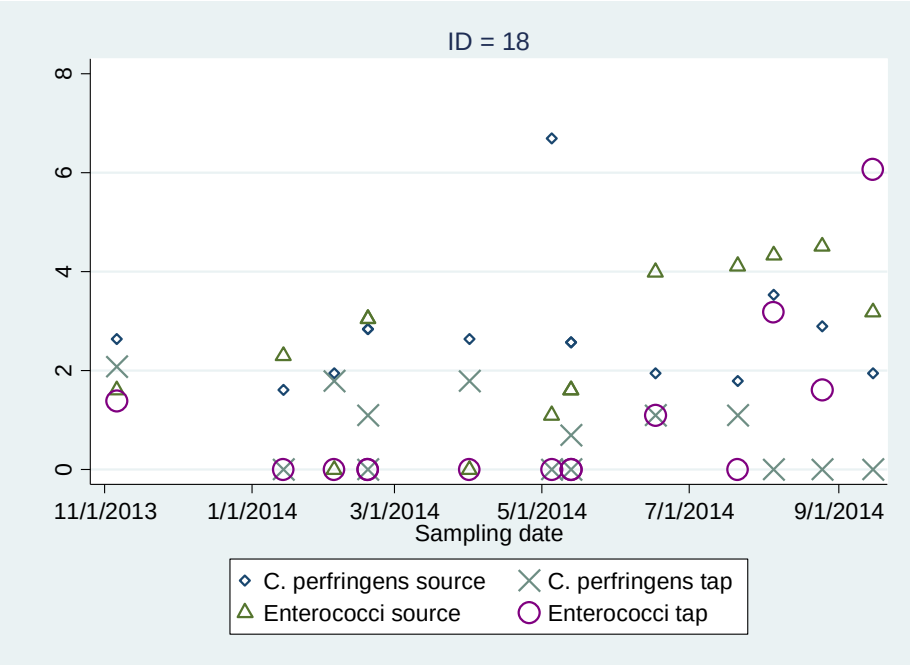


Figure 3.40 *C. perfringens* and enterococci (log cfu ml^{-1}) in source and tap waters from sampling site 18, over time

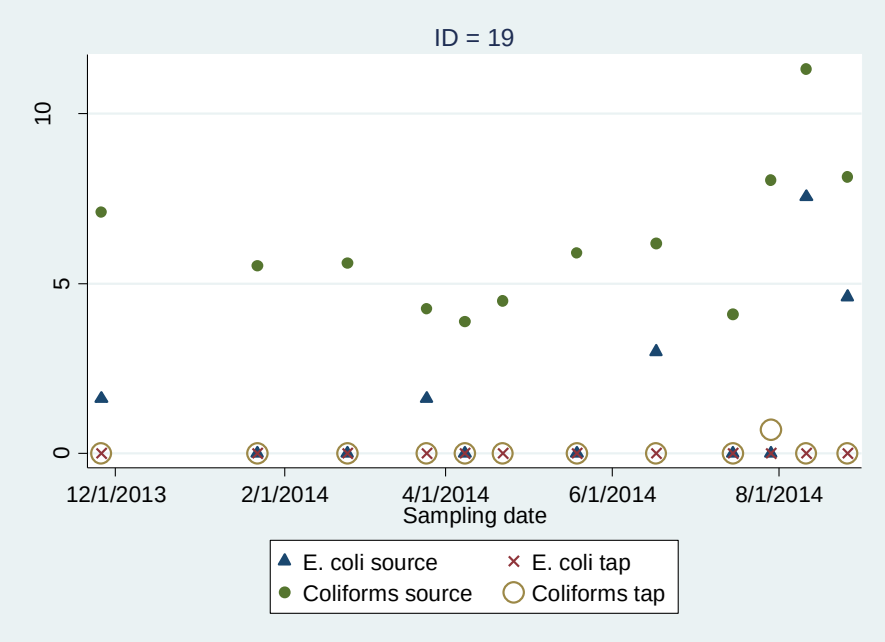


Figure 3.41 *E. coli* and coliforms (log cfu ml^{-1}) in source and tap waters form sampling site 19, over time

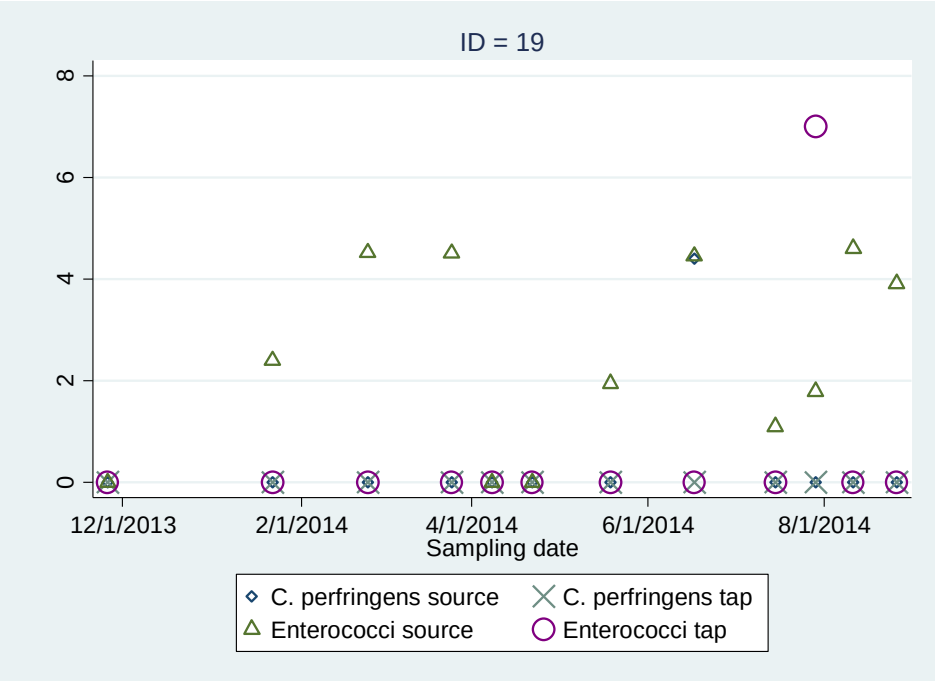


Figure 3.42 *C. perfringens* and enterococci (log cfu ml^{-1}) in source and tap waters from sampling site 19, over time

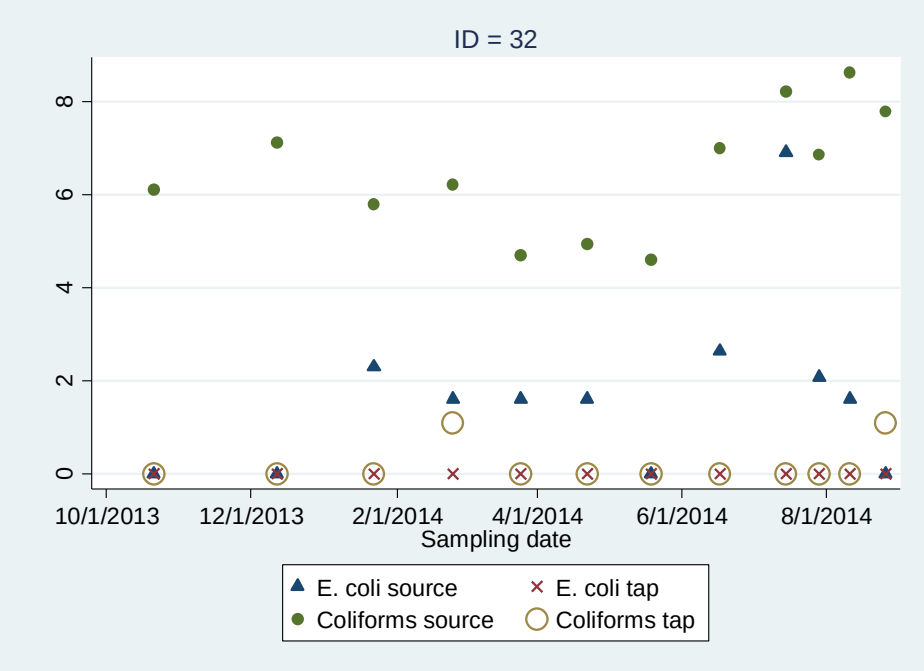


Figure 3.43 *E. coli* and coliforms (log cfu ml^{-1}) in source and tap waters from sampling site 32, over time

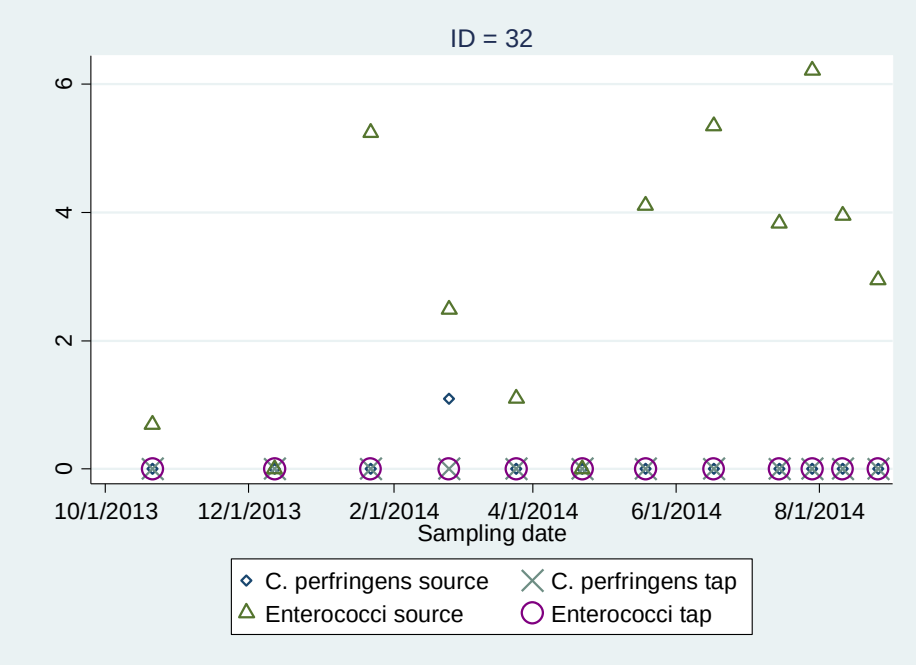


Figure 3.44 *C. perfringens* and enterococci (log cfu ml^{-1}) in source and tap waters from sampling site 32, over time

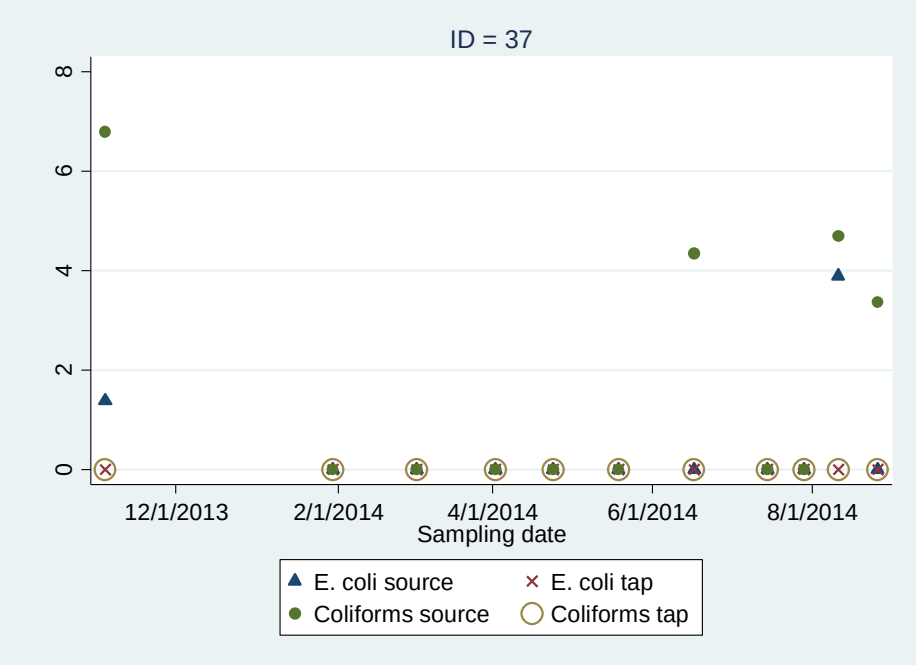


Figure 3.45 *E. coli* and coliforms (log cfu ml^{-1}) in source and tap waters from sampling site 37, over time

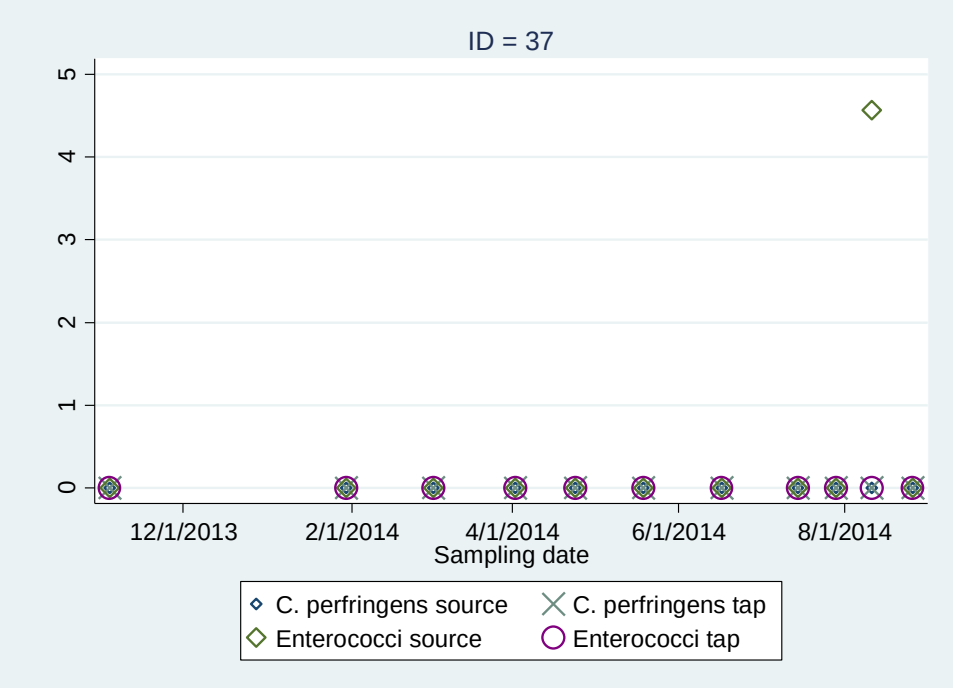


Figure 3.46 *C. perfringens* and enterococci (log cfu ml^{-1}) in source and tap waters from sampling site 37, over time

3.4.4. Soil and weather data

Coliforms and *E. coli* were detected in 90 % and 30% respectively in soil samples tested across 28 sites where soil sampling was possible. Coliform counts were statistically significantly (*P* <0.001; ANOVA) greater in quarters 1,3 and 4 than in quarter 2 (means of log-transformed data: Q1- 2.8 ± 0.2; Q2 2.1 ± 0.3; Q3, 2.9 ± 0.2; Q4; 3.3 ± 0.2). Although not detected in the majority of soil samples overall, *E. coli* counts were significantly (*P* = 0.010; ANOVA) greater in Q4 (means of log-transformed data: Q1- 0.3 ± 0.2; Q2 0.4 ± 0.2; Q3, 0.3 ± 0.1; Q4; 1.1 ± 0.3). This could relate to livestock grazing being more prevalent during spring/summer (Q3 and 4). The substantial rainfall experienced during Q4 may increase transmission of faecal material by overland flow resulting in generally higher incidence of E. coli in soils during Q4 – a result of the combined effects of livestock grazing and rainfall.

Quarter	Dates	Average monthly rainfall for sampling period (mm)			Days rain >1mm	Summary
		North	East	West	All	
1	Oct-Dec 2013	230.2	148.1	239.6	20.4	Mostly unsettled, mild spells, some dry periods, snow on higher ground, some very wet windy weather.
2	Feb/March 2014	178.5	126.5	231.5	19.4	Major winter storms, few dry days, unsettled.
3	May 2014	100.7	69.3	130.5	15.9	Generally unsettled month with rain and some heavy and occasionally thundery showers
4	August 2014	241.6	154.4	158.7	19.2	Generally unsettled with a mix of rain and showers

Table 3.14 Weather during sampling periods (derived from Met Office Regional Summaries (http://www.metoffice.gov.uk/climate/uk/summaries/2014/may)

3.5. Statistical analyses

A full statistical analysis was only possible on the quarterly data, due to the limited number of sites from which monthly data were available.

3.5.1. Statistical analyses of quarterly data

Logistic regression models were fitted to the following binary response variables: failure, microbiological failure, chemical failure, presence of tap confirmed *E coli*, presence of tap confirmed coliforms, presence of tap confirmed Enterococci and presence of tap confirmed *C. perfringens*. As measurements were taken from the same supply in each quarter, a generalized linear mixed model was used with a random effect for the supply.

Potential explanatory variables that had a highly skewed distribution were log-transformed prior to inclusion in the analysis. The following explanatory variables were considered: seasonality (categorical variable for the four quarters), tap conductivity, tap pH, log(tap TOC), log(tap turbidity), log(tap Al), log (tap Fe), log(tap Mn), log (source presumptive *E coli*), log(source presumptive coliforms), log (source presumptive Enterococci), log(source presumptive *C. perfringens*), source conductivity, source pH, log(source TOC), log(source turbidity), log(source Al), log (source Fe), log(source Mn), and years since installation. For the model of chemical failure tap Fe, tap Mn, tap Al, tap pH and tap turbidity were excluded as possible explanatory variables since high values of these and low values of pH are direct causes of chemical failure.

Initially colour, UV transmittance and filtered TOC were also considered as possible explanatory variables but as these were highly correlated with TOC it was not possible to include all these variables in the model and TOC was selected. Correlations between log-transformed values of these four variables for the source are shown below.

Correlations

logTOC_s	1	-			
logf_toc_s	2	0.9802	-		
logcol_s	3	0.8939	0.8965	-	
loguvtrans_s	4	-0.7774	-0.7746	-0.8758	-
		1	2	3	4

There is a significant relationship between source TOC (log-transformed) and failure, microbiological failure, chemical failure, presence of ecoli and presence of *C. perfringens*. There is a significant relationship between the source presumptive *E. coli* (log transformed) and the presence of both coliforms and enterococci. Microbiological

failure and the presence of ecoli are both related to the source presumptive *E. coli* (log transformed) as well as to the source TOC (log-transformed), but as there is a moderately strong correlation (0.42) between these two variables they are not both significant if both are included in the model.

4. Laboratory study on UV effectiveness

4.1. Aims and objectives

Due to the various practical constraints on the design of the PWS monitoring programme (as discussed in Section 3.2) it was not possible to sample from and monitor PWS representative of the entire range of source water typologies used as PWS in Scotland. Also, as with any field study, it was impossible to control for a myriad of different factors that may contribute to water quality. Due to these two reasons, it was decided to conduct a laboratory trial to investigate the efficacy of UV for deactivation of *E. coli* across a selection of possible water typologies not covered as part of the PWS monitoring programme (described in Section 3). The main hypotheses of this experiment were:

1. Die-off will increase with increasing levels of UV irradiance.

2. Water typology will impact on levels of die-off. Specifically waters with greater turbidity levels will provide enhanced protection against UV radiation and favour survival.

The aims of this experiment were to:

1. Investigate the efficacy of UV light to deactivate *E. coli* in a range of water typologies including the effect of turbidity (NTU), water pH, trace element concentrations, and other factors.

2. Plot dosimetry curves (see Section 2.3.2) for each water typology by measuring *E. coli* deactivation over a range of different UV doses.

3. Extrapolate these laboratory results to the main PWS monitoring dataset, i.e. the dosimetry curves provide the relationships between various water quality parameters and UV efficacy. These relationships can then be applied to the main monitoring data in order to make inferences about the effectiveness of UV treatment across all monitored PWS within this project.

4.2. Study design

This experimental work had four main phases:

1. Statistical analyses of the PWS monitoring data against the main PWS database provided by Scottish Government to identify water typologies that were under-represented by the PWS monitoring campaign.

2. Geochemical modelling was then undertaken in order to develop realistic recipes for each water typology of interest. The aim was to develop recipes that would result in waters that were realistic in the environment, chemically stable, and likely to be used as sources for PWS.

3. Uridine actinometry was undertaken to estimate the dose of UV light provided by a lab-mounted UV bulb for a given exposure time. This work was then used to derive exposure times by which to expose each water typology to in order to subject it to a specific dose of UV.

4. Each of the water typologies 'created' in '2' above were spiked with *E. coli* and exposed to a range of UV doses derived from the actinometry work ('3' above).

4.3. Water typology selection

An analysis of gaps was undertaken on the Scottish Government PWS database. It was considered that turbidity, colour and pH were the most important parameters associated with UV transmittance. The distributions of these three parameters within the Scottish Government database were converted to categorical variables "high", "medium" and "low". This resulted in 27 possible combinations of turbidity, colour and pH conditions (Table 4.1). For each combination, the full Scottish Government data base was interrogated to identify the number of supplies for each combination of conditions. This information was then used to predict the number of supplies of each combination that would be expected in the sub-sample of 35 sampling sites included in the PWS monitoring programme. Where representation was statistically significantly different from what would be expected based on the analysis of the dataset, these water typologies were identified as a gap in our monitoring programme and were put forward to be considered in this laboratory study. In total, 12 combinations of turbidity, colour and pH were identified (Table 4.1). These different combinations were then further investigated using geochemical modelling to investigate the feasibility of these waters being used as PWS based on factors such as chemical stability.

Table 4.1 Summary of gap analysis – entries highlighted indicate water typologies not represented by the PWS monitoring sub-set

turbidity	colour	pH	database	expected in our sub-set	observed
low	low	low	25	1.8	3
low	low	medium	27	1.9	8
low	low	high	34	2.4	6
low	medium	low	6	0.4	1
low	medium	medium	6	0.4	3
low	medium	high	16	1.1	2
low	high	low	3	0.2	1
low	high	medium	2	0.1	0
low	high	high	2	0.1	0
medium	low	low	17	1.2	0
medium	low	medium	27	1.9	1
medium	low	high	27	1.9	1
medium	medium	low	18	1.3	0
medium	medium	medium	23	1.6	1
medium	medium	high	34	2.4	0
medium	high	low	27	1.9	0
medium	high	medium	18	1.3	1
medium	high	high	19	1.3	1
high	low	low	12	0.8	0
high	low	medium	16	1.1	0
high	low	high	10	0.7	0
high	medium	low	10	0.7	1
high	medium	medium	11	0.8	0
high	medium	high	19	1.3	0
high	high	low	30	2.1	0
high	high	medium	33	2.3	3
high	high	high	25	1.8	2

4.4. Geochemical modelling to develop water typology recipes

Geochemical modelling was undertaken to design a series of water typologies representative of the 12 potential 'gaps' identified above (Section 4.3). It was important that the final water typologies were chemically stable and that the specific combinations of pH, colour, turbidity, and the other major ions expected in the waters did not give rise to any chemical reactions, precipitate formation, etc.

The modelling considered the following measured data from the Scottish Government data base as input parameters:

- Chloride
- Colour
- Conductivity
- pH
- Iron
- Manganese
- Sodium
- Total Organic Carbon (TOC)
- Turbidity

A chemical speciation model was used to estimate concentrations of important elements both in terms of their total concentration, and the total dissolved concentration which is the sum of any inorganic complexes plus any dissolved organic complexes. The following elements were modelled (Table 4.2):

Table 4.2 Modelled parameters as output from the geochemical modelling

Element	Total	Total dissolved	Dissolved inorganic complexes	Dissolved organic matter	Precipitated in mineral form
Iron (Fe)	Fe^{3+}_{total}	Fe^{3+}_{diss}	Fe^{3+}_{inorg} (Σ Fe^{3+}, $FeOH^{2+}$, etc.)	$Fe^{3+}_{DHA\_PartI}$	Ferrihydrite
Manganese (Mn)	Mn^{2+}_{total}	Mn^{2+}_{diss}	Mn^{2+}_{inorg}	$Mn^{2+}_{DHA\_PartI}$	Rhodochrosite
Sodium (Na)	Na^{+}_{total}				
Chloride (Cl^-)	Cl^-_{total}				

From this modelling exercise a total of 8 water typologies were identified that were both gaps in our PWS monitoring programme, as well as being chemically stable and thus likely to be used as a source of water for PWS (Table 4.3).

Table 4.3 Recipes for the 8 water typologies used in the UV dosimetry experiments

pH	TOC mg l^{-1}	Ferrihydrite µg l^{-1}	Fe^{3+}_{diss} µg l^{-1}	NO^{3-}_{total} mg l^{-1}	Na^{+}_{total} mg l^{-1}	Cl^-_{total} mg l^{-1}	Turbidity NTU
6.28	0.0	94	1.2	0.071	2.3	3.02	
6.91	10	0.0	224.0	0.168	6.9	7.10	
7.16	20	0.0	448.0	0.336	13.8	14.20	
7.15	5.0	0.0	0.0	0.000	2.3	0.00	
5.78	40	0.0	0.0	0.000	4.6	0.00	
7.32	40	0.0	0.0	0.000	6.9	0.00	
7.21	1.0	0.0	5.6	0.004	2.3	0.18	4.00
7.10	1.0	0.0	28.0	0.021	2.3	0.89	8.00

These 8 water typologies were prepared in the laboratory. The turbidity of the waters was adjusted through the addition of humic acids. It was found that commercially

available humic acid had an unacceptable ash content that caused an imbalance in the water recipes. Due to this, peat was collected from the Moss of Fishrie in North Aberdeenshire (Grid Reference NJ835593; Figure 4.1) as previous research into this area of hill peat by the James Hutton Institute had revealed that it has unusually low ash content.

Figure 4.1 Peat sampling at the Moss of Fishrie, Aberdeenshire (Grid Reference NJ835593)

4.5. Uridine actinometry

The final dosimetry study was to be undertaken using a UV irradiation box (Figure 4.2), a piece of laboratory equipment designed to deactivate microorganisms in samples or to sterilise equipment being used within a microbiological laboratory. The dosimetry experiment required that the water typologies are exposed to increasing levels of UV exposure (see Section 2.3.2 for an explanation of dosimetry). In order to do this, it was important to first calculate the UV dose received per unit time. This was done using uridine actinometry, an approach to measuring the intensity of incident UV radiation by

measuring the degradation of uridine exposed to UV light. As uridine degrades upon exposure to UV at a known rate, it is possible to relate reduction in uridine to UV intensity.

Figure 4.2 UV Irradiation Box

As discussed above, it was important to know the UV dose received by our samples when irradiated in the irradiation box for a given period of time. UV dose per unit time is also known as the fluence rate, W m^{-2}. For monochromatic light, the intensity *I* (Einsteins s^{-1}) can be determined experimentally by actinometry (see Figure 4.3):

$$I = \frac{\Delta U}{\Phi T}$$

Where ΔU is the change in the number of moles of uridine measured at time point 1 compared to time point zero, Φ is quantum yield (mol $Einstein^{-1}$), T is time (s), and A is the irradiated area (m^2). The quantum yield of uridine irradiated by UV light at either 254 or 262 nm is well known from the literature and is equal to 0.019 mol $Einstein^{-1}$.

Once *I* (Einsteins s^{-1}) has been determined, this measure can then be converted to *I* (W m^{-2}) using the following formula:

$$I\ (W\ m^{-2}) = \frac{I\ (Einsteins\ s^{-1}) \left(\frac{\Delta U}{\lambda}\right)}{A}$$

Where λ is the wavelength of UV light (either 254 or 262 nm), and A is the area irradiated (m^2).

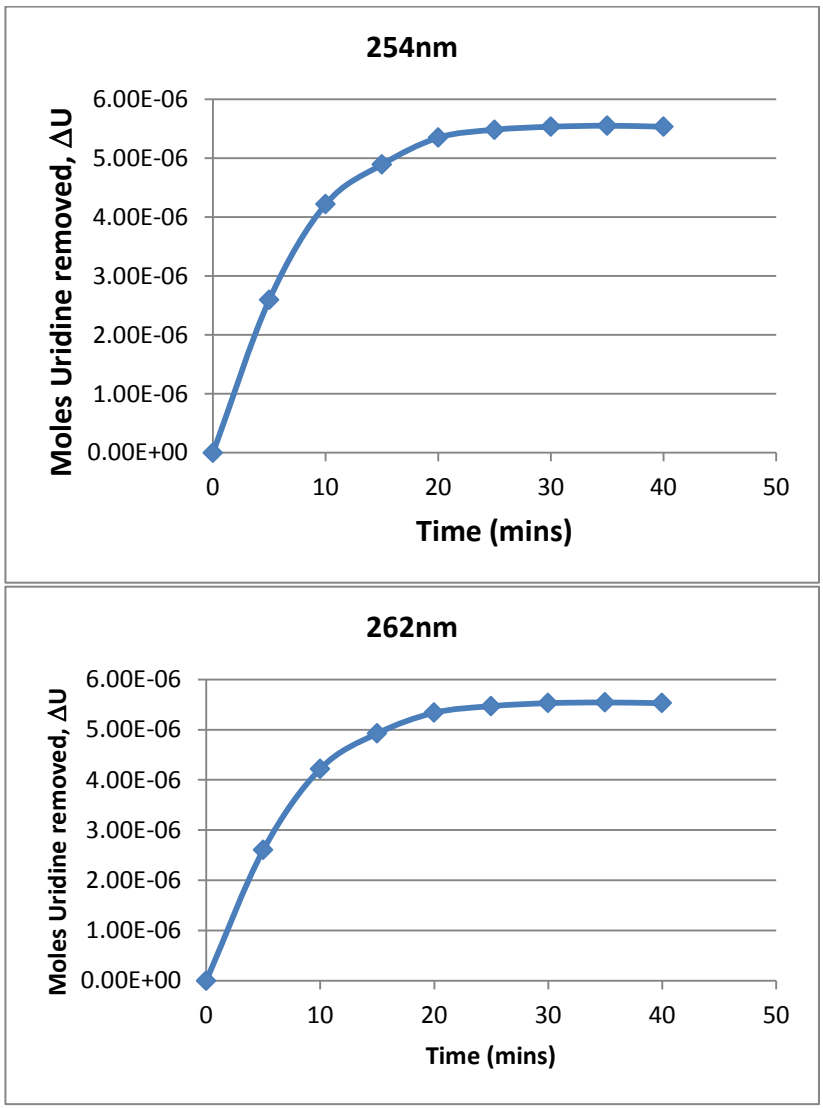


Figure 4.3 Moles of Uridine removed (ΔU) with irradiance time in the irradiation box set at W

These data were then used to determine the following irradiance times to use in the dosimetry experiment (Table 4.4):

Table 4.4 Irradiance times used in dosimetry experiment (the operating range of typical domestic UV installations is usually between 30 and 40 mJ cm^{-2})

Irradiance mJ cm^{-2}	Time of irradiance On irradiation box (min)
10	0.2
20	0.3
30	0.5
40	0.7
50	0.8

4.6. Laboratory procedure

Each water typology was spiked with the same amount of *E. coli* strain ATCC25922. This is a clinically derived reference isolate of clonal group B2 and as such is not known to have any pathogenicity factors and is therefore a low risk organism to work with in the laboratory. The relationship between optical density, and cfu was ascertained experimentally and this was used to ensure that each water typology sample received the same number of *E. coli*. Using this approach, an *E. coli* stock solution of 1 x 10^8 cfu ml^{-1} was prepared.

A pre-experiment was run to iron out any issues and to refine the experimental protocol. 2.5 l of each water typology was made up according to the recipes described in Table 4.3. Each typology was gently mixed using a magnetic stirrer to ensure that any particulates were evenly distributed. Whilst stirring, 1 ml of the *E. coli* stock solution was then added to each of the 2.5 l water samples in order to give a final concentration of approximately 1 x 10^4 – 1 x 10^5 cfu ml^{-1}. A sub-sample of 150 ml was taken from each spiked water typology and each placed in separate petri dishes for irradiation. These were irradiated in the irradiation box set to 2020 W m^{-2}. Samples were irradiated at a range of different times as detailed in Table 4.4. On removal from the crosslinker, 0.5 ml was sampled and diluted with buffer to eventually provide final concentration of 1 x 10^2 cfu ml^{-1}. These diluted samples were then assayed for coliforms and *E. coli* using the colilert methodology that has been used throughout this project.

4.7. Results and conclusions

Even the lowest UV dose rate was able to deactivate 100 % of *E. coli* used in this experiment. The entire experiment was run three times, and the results were the same on all occasions. It is possible that the lab strain (used in order to maintain Category II health and safety compliance) of *E. coli* used was more susceptible to UV light than typical environmental strains. However, an independent expert on UV disinfection (Dr. Thalia Chatzisymeon, University of Edinburgh) confirmed that total deactivation could be expected in less than 10 seconds using an 11 W UV bulb (this was elucidated during work looking into the potential use of UV disinfection for *E. coli* removal in a food processing factory), far lower wattage than those used in PWS treatment systems. It was her opinion that most bacterial fails from UV treatment systems were either associated with poor maintenance or dark reactivation (see Section 2.2) where treated water is subsequently stored in e.g. holding tanks.

5. Overall Conclusions

Due to the complex nature of the data, a wide range of conclusions or potential new hypotheses can be generated, and to a large extent these have been discussed in the preceding text. Returning to the aims and objectives of this study, the following main conclusions can be drawn from our data:

1. Quarterly sampling should be sufficient to gain a reasonable appraisal of water quality at a given site for the purposes of determining whether treatment systems are adequate

2. Domestic-scale UV systems (30 – 40 mJ cm^{-2}) are effective at deactivating *E. coli* in a range of waters typical of those found in Scotland. They should remain effective even if irradiation drops as low as 10 mJ cm^{-2}

3. Bacterial failure of tap water is most strongly correlated with source water TOC; i.e. high TOC source waters are more likely to result in bacterial fail at the tap

4. TOC is highly related to colour and turbidity; all of which affect UV transmittance

5. Bacterial failure of tap water is more likely to occur if levels of TOC in source waters increase, e.g. during/after heavy rain events

6. Source waters located in catchments dominated by extensive or intensive livestock grazing seem to be more vulnerable to compromised tap water quality

7. In agreement with 3 and 4 above, source waters located in catchments dominated by extensive or intensive livestock grazing are more likely to have elevated levels of TOC

8. Water supply types that have greater connectivity to the surface environment (surface supplies, shallow wells) are more vulnerable to fluctuations in TOC, and hence bacterial fail at the tap

9. Where treatment systems are well maintained (filters and UV bulb), risk of bacterial failure of the tap water is much reduced. Well maintained treatment systems show considerable robustness to fluctuations in source water bacterial loads

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7. Appendices

7.1. Use of UV for water treatment

7.1.1. UV Standards

USEPA UV Disinfection Guidance Manual (UVDGM)
The UVDGM provides comprehensive guidance on the use of UV for water treatment. It contains information applicable to users, equipment suppliers, and regulators. It is not a statutory document, and US water utilities are not obligated to follow its recommendations for good practice. Although written in the context of US water quality regulations, with particular reference to the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), the manual is essentially a good practice guide and, as such, its relevance is not restricted to the US. The authority for the LT2ESWTR is derived from the Safe Drinking Water Act (SDWA) as amended in 1996, which applies to public water systems defined as those serving at least 25 people.

The manual is arranged in six sections, the first of which is an introduction and summary of the pertinent US water treatment regulations. The second section is an overview of UV disinfection, including descriptions of microbial response to UV and of the components of UV systems; and a discussion of other water quality effects and by-product formation. The remaining sections consider the steps required to implement UV disinfection, from initial planning and design through to operation and validation. Detailed supporting information, case studies and a discussion of lamp break issues are appended.

The implementation sections are outlined below.

Section 3: Planning analyses for UV facilities
This section discusses what should be considered at the planning stage:

- defining UV disinfection goals;
- where to incorporate UV into a treatment train;
- defining design parameters;
- the characteristics of different types of UV lamp;
- control strategies;
- validation issues;
- headloss constraints;
- estimating footprint (in terms of what equipment to allow for);

- estimating costs (in terms of what equipment to allow for).

Section 4: Design considerations for UV facilities
This section discusses the key factors that should be considered when undertaking detailed design:

- hydraulics;
- operating approach;
- instrumentation and control;
- electric power supply;
- layout;
- specifications for equipment.

Section 5: Validation of UV reactors
This section, together with supporting appendices, describes in detail the UVDGM's recommended biodosimetry validation protocol:

- minimum requirements for validation;
- selection of challenge micro-organisms;
- equipment requirements;
- determining test conditions;
- test methodology;
- analysis of results;
- reporting;
- evaluating the need for re-validation.

The rationale behind the protocol is given. Quality assurance and quality control are discussed.

Section 6: Start-up and operation of UV facilities
This section discusses commissioning and operation of UV plants:

- commissioning;
- operation;
- maintenance;
- monitoring and recording operating data;
- staffing, training, safety.

Austrian standard ÖNORM 5873; Parts 1-2
ÖNORM 5873-1 'Plants for disinfection of water using ultraviolet radiation – Requirements and testing: Low pressure mercury lamp plants (1/3/2001)'

ÖNORM 5873-2 'Plants for disinfection of water using ultraviolet radiation – Requirements and testing – Part 2: Medium pressure mercury lamp plants (1/8/2003)'

Scope

The ÖNORM standards set out the requirements for the design, testing, operation and monitoring of UV systems for the treatment of drinking water. The standards include a comprehensive definition of all of the technical terms used.

ÖNORM 5873-2 is derived from, and has much in common with, ÖNORM 5873-1, but does include some important differences that reflect its application to medium pressure UV systems.

Requirements

The standards require that a 'Reduction Equivalent Fluence' (REF) of 400 J m^{-2} (40 mJ cm^{-2}) is delivered, relative to a wavelength of 253.7 nm, at a given flow rate and water quality (UV transmittance). It is stated that this dose is sufficient to achieve a 6 log reduction of health related water transmittable bacteria and a 4 log reduction of health related water transmittable viruses 'according to the state of the art'.

The water to be treated by UV must conform to the physical and chemical aspects of the EU Drinking Water Directive, which has implications for the positioning of the UV system.

The standards set out requirements for:

- the irradiation chamber;
- monitoring;
- control.

Type tests

The standards describe type tests to be used to independently verify that UV systems achieve the performance claimed by the manufacturer (the operating conditions – UVT and flow rate - which enable a Reduction Equivalent Fluence (REF) of 40 mJ cm^{-2}). Tests can be performed off-site or on-site. In the former case, the results are accepted for the particular system being tested; results from an on-site test apply only to that installation.

Type tests have five parts:

- compliance against manufacturers specification (REF);
- general characteristics (e.g. electrical current);
- radiation monitoring performance;
- microbiological challenge test (Biodosimeter);
- evaluation of the admissible operating conditions.

To allow for ageing, lamp output is adjusted to that expected at the end of guaranteed lamp life. For off-site tests, the UV system inlet is fitted with a 90° bend to simulate a compromised hydraulic installation.

The standards specify biodosimetry using *Bacillus subtilis* spores. A dose response curve must be determined for each batch of spores, the UV sensitivity of which must lie within stipulated limits. Protocols are given for determining the limiting operating conditions (flow rate, UVT) at which the required REF of 40 mJ cm^{-2} is achieved, which can then be compared against the manufacturer's claims.

Operational Requirements
The standards require that operators of UV systems keep to servicing schedules set out by the manufacturers, and keep appropriate records of operational and service actions.

Testing of a Production Series
ÖNORM 5873-1 sets out conditions under which a range of equipment of essentially the same design but scaled for a different flow rates, referred to as a 'Production Series' can be subjected to a reduced series of tests.

German standard DVGW W294 Parts 1-3
W294-1 UV-devices for the disinfection of the water supply - Part 1: Requirements on the design, function and action (June 2006)
W294-2 UV-devices for the disinfection of the water supply - Part 2: Tests of design, function and disinfection effectiveness (June 2006)
W294-3 UV-devices for the disinfection of the water supply - Part 3: Sensors for the photometric monitoring of UV-Disinfection; tests and calibration (June 2006)

Scope
The 2006 German standards are not yet available as an English translation, however it is understood that they are similar in concept to the Austrian standards, requiring:

- validation of a dose of 400 J m^{-2} (40 mJ cm^{-2});
- validation by biodosimetry using *Bacillus subtilis* spores.

European Standard EN 14897:2006+A1:2007
Water conditioning equipment inside buildings – Devices using mercury low-pressure ultraviolet radiators – Requirements for performance, safety and testing (June 2006). Published in the UK as BS EN 14897:2006 + A1:2007 by BSi.

Scope
This standard relates to UV devices which are permanently connected either to the mains supply at the point of entry into a building, or to the water distribution system within a building, and as such are clearly not intended for municipal water treatment

applications. The scope as defined also does not apply to private water supplies. The standard includes a comprehensive definition of all of the technical terms used.

Requirements
The requirements, including materials of construction and design requirements are principally the same as defined in ÖNORM 5873-1.
The standard sets out detailed electrical control and monitoring requirements, distinguishing between units for disinfection and units for bactericidal treatment. The requirements for the former are more onerous and include the requirement to monitor UV intensity.

Testing
'Type Tests' are similar to those specified in the ÖNORM standard for low pressure UV systems. The UV dose target is 40 mJ cm^{-2}, irrespective of whether the unit is intended for disinfection of bactericidal treatment. The standard implicitly requires the use of *Bacillus subtilis* spores for the biodosimetry; although the only explicit reference to *Bacillus subtilis* is as an example test organism in the Definitions, the permissible UV sensitivity range of the biodosimeter stipulated in Annex B is recognisably that given for *Bacillus subtilis* in ÖNORM 5873-1.

US NSF/ANSI Standard 55 – 2012
Ultraviolet microbiological water treatment systems (August 2012).

Scope
This standard applies to point of entry and point of use UV equipment installed in single private residences. Its purpose is to establish minimum requirements for the reduction of micro-organisms using UV. It distinguishes between Class A systems, which are intended for the inactivation of pathogenic micro-organisms, and Class B systems, which are intended only for 'supplemental bactericidal treatment of public or other drinking water that has been deemed acceptable by a local health authority'.
Its scope also encompasses materials of construction, integrity (under pressure), product literature, equipment labelling and service obligations of manufacturers.

Requirements
The standard requires that a flow-limiting device be fitted that prevents the flow rate exceeding the maximum specified for the unit at the maximum specified operating pressure.
Class A systems must deliver a dose of 40 mJ cm^{-2} at a defined minimum UV transmittance and must be fitted with a UV sensor that will trigger an alarm if an insufficient dose is being applied. Class B systems must deliver a dose of 16 mJ cm^{-2}.

Testing

Performance must be validated using biodosimetry in accordance with a proscribed protocol, using either MS2 phage (Class A systems) or T1 Coliphage or *Saccharomyces cerevisiae* (Class B systems)[2]. Collimated beam tests are required to determine the dose response curve of each batch of challenge micro-organisms.

The protocol requires parallel testing of 2 UV units over 7 days. Flow rate must equal the maximum allowed by the integral flow-limiting device. The quality of the test water is specified, including a minimum UV transmittance of 96%. The transmittance must then be reduced using parahydroxybenzoic acid (PHBA) to 70% or until the alarm point is reached, whichever results in the lower transmittance, and kept at this value for the duration of the test.

Samples must be taken during periods of steady-state operation and immediately on start-up after overnight stagnation periods. The calculated log reduction is derived from the geometric mean of all influent sample counts and the geometric mean of all effluent sample counts, and must be equal to or greater than the log reduction at 40 mJ cm^{-2} read from the dose response curve.

Class A systems validated in accordance with this standard can claim effective inactivation specifically of *Cryptosporidium* oocysts and *Giardia* cysts. They cannot claim wider effectiveness against cysts in general unless preceded by another treatment stage for removal or inactivation of cysts that complies with the appropriate NSF/ANSI standard, nor can they make claims of reduction of the challenge micro-organism. Class B systems can only claim effectiveness for non-pathogenic, nuisance micro-organisms.

NWRI/WRF guidelines

The US National Water Research Institute (NWRI), in collaboration with the Water Research Foundation (WRF) has produced UV disinfection guidelines for drinking water and water reuse (NWRI, 2012). These provide an overview of UV system design and operation, with outline guidance, together with protocols for dose validation tests using MS2.

Comparison of dose validation requirements of ÖNORM standard and UVDGM

A comparison of key elements of the UVDGM and ÖNORM validation methodologies is given in Table A.1 (the DVGW and ÖNORM standards being equivalent).

The UVDGM and European approaches are both designed to demonstrate that a UV reactor will achieve a specified performance under given operating conditions. But in comparing the two, it should be recognised that they have fundamental differences.

[2] The option of using T1 Coliphage for Class B system validation was introduced in 2012, with the stated intention to eliminate the use of *Saccharomyces cerevisiae* after September 2017.

The UVDGM approach is concerned with validating UV for some specified log inactivation of a given pathogen, which follows the established US EPA methodology of assigning log inactivation credits to treatment processes. The lower the target inactivation, the smaller the UV plant will be, since the required Validated Dose will be smaller.

The European approach is concerned with UV as the primary disinfection treatment stage. A target REF (or RED) of 40 mJ cm^{-2} is stipulated, justified on the grounds that such a dose is sufficiently high for adequate inactivation of health-related bacteria (6 log) and viruses (4 log) according to current knowledge.

Table 7.1 Comparison between UVDGM and ÖNORM validation methodologies

	UVDGM	ÖNORM
Validation method	Biodosimetry	Biodosimetry
Target dose	Depends upon target pathogen and log removal credit, for which values of target dose are tabulated.	40 mJ/cm^2
Challenge micro-organism	Not specified	*Bacillus subtilis* ATCC 663 spores, with stipulated bounds within which dose-response curve must lie.
UV intensity sensors	Recommends that the reading of each plant sensor should differ by no more than 10% from the mean reading of two or more recently calibrated reference sensors, in the same sensor port with the same lamp, lamp power and UVT. However, the methodology allows for a greater uncertainty provided it is incorporated into the Validation Factor.	Stipulates that the uncertainty in plant sensor reading shall be taken as 15% unless a higher value is demonstrated. Specifications for measuring range and resolution of plant sensors are given.
Lamp ageing	Lamp output must be that expected at the end of the lamp utilisation period. Simple turn-down is acceptable if *either* the manufacturer confirms that this approach is adequate, *or* if tests demonstrate that lamp ageing is uniform. If there is evidence of non-uniform lamp ageing, then used lamps that have been operated under similar conditions should be fitted for the	Tests shall be conducted with new lamps that have in service for 'about 100 hours'. Lamp output must be lowered to the value at the end of the lamp utilisation period. The manufacturer must specify how output is to be lowered (the fitting of mesh screens, or substitution of an alternative ballast, are permitted), and by how much.

	validation tests.	An illustrative figure of 30% is given *only as an example*.
Applicability of validation	A recommended Validation Report structure and checklist are provided. The Validated Dose, log removal credit achieved, validated operating conditions, and validation test operating conditions (including flow rate, UVT and lamp power) must be included.	The maximum flow, minimum UVT and minimum reference irradiance as determined by the validation test must be stated on identification plates attached to the UV reactor. The operating range of the plant in terms of these three parameters must be provided in graphical, analytical and table form.

7.1.2. Pre-treatment

Successful application of UV requires the source water quality to meet regulatory and practical criteria. The distinction is made primarily because the regulatory colour limit of 20 ^{o}H that applies to Type A private supplies does not apply to Type B supplies, but, as has been shown in Section **Error! Reference source not found.**, it represents the practical limit for UV application. Similarly, while Type B supplies are not constrained by the regulatory limits for iron (200 μg l^{-1}) and manganese (50 μg l^{-1}) that apply for Type A supplies, excessive concentrations of either may result in fouling of UV lamps and thus reduced output.

Turbidity

The absolute regulatory limit for turbidity of 4 NTU applies to Type A and B supplies, with Type A supplies subject to the additional requirement of achieving 1 NTU 'whenever possible'. Reputable suppliers of UV disinfection equipment specify that there should be a 5 μm filter upstream of the UV unit, and filtration to this level should ensure compliance with the turbidity limit. Cartridge filters of this rating are readily available, and UV should not be installed without one. Depending on source water quality, it may be necessary to install a coarser filter upstream to prevent the 5 μm filter from blinding too quickly.

Colour

Elevated colour resulting from the passage of water through peaty soils is common in Scotland. For private supplies the likely treatment options are adsorption on granular activated carbon (GAC) or bone char, and ion exchange.

Filters containing GAC or bone char are the simpler option, but the adsorbent media will become exhausted over time – the useful life depending upon influent colour, the contact time between water and the filter media, and the cumulative volume of water treated. Once exhausted, the filter must be replaced.

The alternative is filtration through a bed of ion exchange resin. Ion exchange makes use of the fact that the organic molecules responsible for colour carry a negative charge. Resins designed for this application contain loosely-bound, negatively charged, chloride ions. The organic molecules are adsorbed from the water onto the resin, which in exchange releases chloride ions into the water. This process can be reversed by bringing the resin into contact with a concentrated solution of common salt, which causes the release of the organic molecules from the resin in exchange for chloride ions. This provides the means of regenerating the resin in-situ.

Iron and manganese

Groundwater sources may contain dissolved iron or manganese. Type A supplies are subject to limits of 200 μg l^{-1} and 50 μg l^{-1} respectively, essentially for aesthetic reasons; both are liable to precipitate and cause staining of surfaces. The precipitation of iron or

manganese on a UV lamp will reduce its output. The dissolution of iron and manganese occurs in depleted-oxygen environments, and to precipitate them requires oxidation. For iron, simple aeration may be sufficient, but for manganese the kinetics are impracticably slow unless the pH is increased and/or a catalyst is used. Filters are available which combine aeration with a catalytic media.

Maintenance

Any additional treatment installed upstream of UV will impose responsibilities on the owner to ensure adequate maintenance. Any advice and user instructions provided by the supplier should be adhered to. This may include replacing filters or media after a certain time or cumulative volume treated. If ion exchange is used, the regenerant solution must be routinely topped up.

7.1.3. Site visit information

JHI provided WRc with photographs taken during site visits to 30 properties. At one property no UV unit was visible in the photographs. Of the remaining 29 properties the suppliers of the UV units were identifiable for 20, Table 7.2.

Table 7.2 UV units identifiable from photographic records of site visits.

Site ID	UV unit supplier	Model	Notes
1	DaRo UV Systems		4 lamp
2	LIFF		1 lamp. A second UV unit, treating a different supply, unidentified.
3	??		1 lamp.
4	Wedeco	Aquada UV Altima	1 lamp
5	Wedeco		1 lamp
7	??		1 lamp
8	Aqua Cure	ACUV	1 lamp
9	LIFF		1 lamp
10	LIFF		1 lamp
11	I & E Smith Services	15W	1 lamp
13	??		1 lamp
14	Filpumps		1 lamp
15			No UV unit in photographs.

Site ID	UV unit supplier	Model	Notes
17	Filpumps		1 lamp
18	??		1 lamp
19	GRC AquaTech		1 lamp
20	I & E Smith Services		1 lamp
21	Filpumps	UV405 BA	1 lamp
24	??		1 lamp
25	Filpumps	UV412	1 lamp
27	GRC AquaTech	Ultraviolet Power UV6	1 lamp
28	??		1 lamp
29	??		1 lamp
30	Sterilight		1 lamp
31	??		1 lamp
32	Filpumps	UV405 BA	1 lamp
33	Filpumps	UV440	1 lamp
34	??		1 lamp
35	Sterilight		1 lamp
36	GRC AquaTech	W Watts	1 lamp

The suppliers identified in this sample of properties are summarised in Table 7.3.

Table 7.3 Suppliers of UV units identified in site visits.

Supplier	Number	Notes
Aqua Cure	1	
DaRo UV Systems	1	
Filpumps	6	
GRC AquaTech	3	
I & E Smith Services	2	
LIFF	3	A brand of BWT
Sterilight	2	A brand of VIQUA, a subsidiary of Trojan
Wedeco	2	A brand of Xylem

7.2. Questionnaire

Private Water Supplies Questionnaire – Version 3 (2nd October 2013)

Protocol (Document 1)

This pack should contain the following documents:

1. Protocol (this document)
2. Copy of original invitation letter
3. Permission slip
4. OS Map of property and surrounding area
5. Questionnaire – to be administered by interview to user of water supply
6. Second questionnaire - a self-reporting version of the questionnaire that can be left with the participant if they refuse to take part in the interview
7. Private Water Supply Risk Assessment – to be completed by surveyor
8. Water samples pro-forma

Step 1 - Questionnaire

This questionnaire is to be administered by interview. The aim is to understand the participant's water supply from their point of view. We want to find out how the supply is used to understand any factors that might affect how well the UV treatment system works. We do not want to lead the participant or bias the responses, so it is best to avoid speaking directly about UV treatment and/or water quality/safety.

Make sure all questions are answered – try to avoid leaving blank spaces – if the participant does not respond or refuses to say, mark "no response" or "refused to answer", etc. in the appropriate box.

If the participant does not want to be interviewed, the self-reported version of the questionnaire (document 6) may be left with them and followed up on a subsequent visit.

Introduce the questionnaire by reminding the participant of the invitation letter (show them the copy of the letter as a reminder) and the phone contact leading up to the visit.

"As part of a large project looking at use of private water supplies in Scotland, we're interested to find out about your water supply and how it is used. This work is funded by Scottish Government and Scottish Water"

"Would you be happy to answer a few questions about your water supply and show us any parts of the supply system that are accessible? This should take about 10 – 15 minutes."

"Would you also be happy if we took photographs of any part of the supply system and some water samples?"

"If you're happy for us to do that, please could you sign this permission slip?"

If necessary, remind the participant that all information collected will remain totally anonymous. Once agreement/permission has been sought, administer the questionnaire (document 5), using the notes provided as guidance.

Step 2 – PWS Risk Assessment

Once the questionnaire is complete, carry out the risk assessment as independently as possible with minimal input from the participant, if necessary; the answers gained during the questionnaire interview can be used to inform this assessment.

1. Select the tables appropriate to the type of water supply being assessed (well, surface, borehole, etc.). There should be 2 tables for each type of supply:
    a. A general site survey
    b. A supply survey
    c. For each question, determine if the answer is yes/no/don't know. Circle the corresponding risk category (H/M/L) in the table.
2. For each question, determine the likelihood – likelihood categories are described below the tables. The most practicable approach to this is to go with your best judgement, even though you will not have all the required information in front of you. Ask the participant where necessary
3. Use the GPS or OS map to capture the National Grid Reference of the supply. Sketch the layout of the system (e.g. location of wellhead, storage tanks, etc.) on the OS map and add any other notes of interest (e.g. deer seen close to storage tanks)
4. The remaining information will be completed back at HQ

Step 3 – Water and soil sampling

See water and soil sampling protocols.

Document 5: Questionnaire by interview

Section A – Supply and Use – Can be completed in the home

Question	Response(s)	Notes for interviewer
These questions are about your water supply and how you use it.		Here we want to establish where the source is, and whether the owner knows where the source is.
A1. How many years have you lived in this property?		Open question – write down all responses even if 'not sure'
A2. How many people live in this property?		Open question – write down all responses even if 'not sure'
A3. Are other properties served by your water supply? If 'yes', how many?[A3d]	☐ Yes[A3a] ☐ No[A3b] ☐ Don't know[A3c]	 Mark down number of properties or any other response such as 'not sure'
A4. Who takes overall responsibility for maintaining the water supply?		Open question – write down all responses even if 'not sure'
A5. Do you know where your water supply comes from?	☐ Yes[A5a] ☐ No[A5b] ☐ Not sure[A5c] ☐Don't know[A5d]	Surveyor to mark known or suspected sources on OS map.
A6. How would describe the quality, appearance and taste of your drinking water?		Open question – write down all responses even if 'not sure'
A7. Do you notice any changes in your water? And if so, when does this happen?		Open question – write down all responses even if 'not sure'
A8. Is there anything about your water supply that concerns you? 1. Risk of flooding 2. Risk of contamination	 ☐ Yes[A8a] ☐ No[A8b] ☐Don't know[A8c] ☐ Yes[A8d] ☐ No[A8e] ☐Don't know[A8f]	Open question – write down all responses even if 'not sure'. Also ask/prompt with the following 4 questions.

3. Risks to health from drinking 4. Risk of supply being interrupted	☐ Yes[A8g] ☐ No[A8h] ☐Don't know[A8i] ☐ Yes[A8j] ☐ No[A8k] ☐Don't know[A8l]	
A9. Has it ever been tested? If yes, do you know what the result was?		Open question – write down all responses even if 'not sure'
A10. What is that land used for? What activities take place there? Have you seen wildlife?		Open question – need to make sure participant understands we are talking about the land that may affect the supply. Surveyor to use map/reality to illustrate
A11. How often do you see animals (livestock, domestic, wildlife) access the area around your water source of where the supply is?	☐ Never[A11a] ☐ Sometimes[A11b] ☐ Often[A11c] ☐All the time[A11d] ☐Don't know[A11e]	Surveyor to point at the source (on map/in reality) to avoid confusion between source and other e.g. storage tanks.
A12. How close do the animals come to your water source?		Open question – write down all responses even if 'not sure'
A13. Do you use your supply for:	☐ Drinking[A13a] ☐ Washing[A13b] ☐ Cooking[A13c] ☐Cleaning[A13d] ☐Animal watering[A13e] ☐Irrigation[A13f] ☐Other[A13g]	Tick all that apply If "Other", elaborate
If A13e is ticked, ask Question A14; if not, jump to Question A15		
A14. Is the water used for animal watering treated? If yes, roughly what volume is used for animal watering?[A14d]	☐ Yes[A14a] ☐ No[A14b] ☐ Don't know[A14c]	Open question – all responses should be noted. Might need encouraging with examples such as e.g. 2 bath-tubs per week
If A13f is ticked, ask Question A15; if not, jump to Section B		

A15. Is the water used for irrigation treated? If yes, roughly what volume is used for irrigation?[A15d]	☐ Yes[A15a] ☐ No[A15b] ☐ Don't know[A15c]	Open question – all responses should be recorded. Might need encouraging with examples such as e.g. 10 acres irrigated for wheat during summer

Section B – Treatment and maintenance – ask B1 and move to location of treatment system if appropriate

Question	Response(s)	Notes for interviewer
These questions are about whether your supply is treated and about the treatment system		Try not to lead/bias the responses by suggesting we're interested in pathogens, dirty water, etc.
B1. Does your water supply undergo any treatment?	☐ Yes[B1a] ☐ No[B1b] ☐ Not sure[B1c] ☐Don't know[B1d]	
If answer to Question B1 is "yes", "not sure" or "don't know", ask to be shown the treatment system and ask Question B2; If not, finish questionnaire		
B2. If yes, can you describe the treatment system you have?		Ask participant to show you the treatment system and use this to help them describe it
B3. Is it OK if I make a note of the different components of your treatment system?	Photo Numbers:	Surveyor to write down their own description of the system when it is shown to them. Take photos (ask permission again). Make note of the file number from the camera.

B4. When was your treatment system installed?		Open question – write down all responses even if 'not sure'
B5. Has it been modified since it was installed, and if so what was done and why?		Open question – write down all responses even if 'not sure'
B6. Who installed it?		Open question – write down all responses even if 'not sure'
B7. Has it ever been repaired or serviced by the installation company or any other company?	☐ Yes[B7a] ☐ No[B7b] ☐Don't know[B7c]	
If answer to Question B7 is "yes", ask B8; if not, jump to Question B9		
B8. If yes, how often was this? Tick which best describes it.	☐ Every 6 months or more often[B8a] ☐ Every year[B8b] ☐ Every 1-2 years[B8c] ☐ Every 2-3 years[B8d] ☐ Every 3-4 years[B8e] ☐ Every 4-5 years[B8f] ☐ Less often[B8g] ☐ Never[B8h] ☐ Don't know[B8i]	Show participant the options if this helps
B9. Has it ever been repaired or serviced by you, your family or friends?	☐ Yes[B9a] ☐ No[B9b] ☐Don't know[B9c]	
If answer to Question B9 is "yes", ask B10; if not, jump to Question B12		
B10. If yes, could you describe how you went about this this was done and where, if anywhere, you obtained any parts that you needed?		Surveyor can get participant to show what they did to help explain this. Surveyor to make note which parts of the system the user serviced
B11. If yes, how often was this? Tick which best describes it.	☐ Every 6 months or more often[B11a] ☐ Every year[B11b]	

	☐ Every 1-2 years[B11c] ☐ Every 2-3 years[B11d] ☐ Every 3-4 years[B11e] ☐ Every 4-5 years[B11f] ☐ Less often[B11g] ☐ Never[B11h] ☐ Don't know[B11i]	
B12. Do you ever open the storage tanks or other parts of the system?	☐ Yes[B12a] ☐ No[B12b] ☐Don't know[B12c]	
If answer to Question B12 is "yes", ask B13; if not jump to Question B15		
B13. If yes, why do you do this?		Open question – write down all responses even if 'not sure'
B14. If yes, how often?	☐ Every 6 months or more often[B14a] ☐ Every year[B14b] ☐ Every 1-2 years[B14c] ☐ Every 2-3 years[B14d] ☐ Every 3-4 years[B14e] ☐ Every 4-5 years[B14f] ☐ Less often[B14g] ☐ Never[B14h] ☐ Don't know[B14i]	
B15. How important is it to you that you have a working treatment system?	☐ Not at all[B15a] ☐ Somewhat[B15b] ☐ Quite important[B15c] ☐ Very important[B15d] ☐Don't know[B15e]	
B16. Could you give a reason for your answer?		Reasoning behind answer to B15 – record all answers, even if 'not sure'
B17. Do you notice any changes in your water after servicing?	☐ Yes[B17a] ☐ No[B17b] ☐Don't know[B17c]	
B18. Could you give a reason for your answer?		Reasoning behind answer to B17 – record all answers, even if 'not sure'

Section C – Interaction with treatment system

Question	Response(s)	Notes for interviewer
These questions are about how your treatment system is used, and how it works		
C1. Do you leave the treatment system switched on all the time?	☐ Yes[C1a] ☐ No[C1b] ☐Don't know[C1c]	Interviewer to make distinction between turning the master switch off vs. a system that automatically kicks in when tap is turned – we want to know about the former
C2. With regards to your water supply, do you do anything differently during or following a power cut?	☐ Yes[C2a] ☐ No[C2b] ☐ Sometimes[C2c] ☐Don't know[C2d]	
If answer to C2 is "yes", ask Question C3; if not, jump to Question C4		
C3. If 'yes', could you tell us what you do?		Reasoning behind answer to C2 – record all answers, even if 'not sure'
C4. Would you know if the treatment system has failed or is in need of attention?	☐ Yes[C2a] ☐ No[C2b] ☐ Unsure[C2c] ☐Don't know[C2d]	
If answer to C4 is "yes", ask Question C5; if not, jump to Question C6		
C5. If you answered yes, could you tell us how you know?		Reasoning behind answer to C4 – record all answers, even if 'not sure'
C6. Would you do anything if you were aware that the system had failed/ was in need of attention?		Open question – write down all responses even if 'not sure'
C7. Do you ever take or use pre-treated water?	☐ Yes[C7a] ☐ No[C7b] ☐Don't know[C7c]	Surveyor to point at some form of pre-treatment storage or tap etc. if present.

C8. If ‘yes’, could you tell us why?		Reasoning behind answer to C7 – record all answers, even if ‘not sure’

Many thanks for taking part in our survey!

7.3. Risk assessment protocol

Supply Type **Well** ☐ **Spring** ☐ **Borehole** ☐ **Surface** ☐

Details of supply system and associated water treatment

Source
Comments:

Location Description:

National Grid Reference:

Intermediate Storage Tank
Comments:

Location Description:

National Grid Reference:

Treatment Type and its location

Distribution Pipework Material

Sketch

General Site Survey

Are any of the following known to be present and likely to influence water quality at the source?

ALL SITES		EVALUATION		
		YES	POSSIBLE	NO
1	Is there good evidence of livestock production (rearing, housing, grazing) that may impact on water supply – including poultry?			
2	Has sludge or slurry been applied to remediate land in vicinity of water supply/system?			
3	Are there any sewage effluent lagoons upstream in vicinity of water supply/system??			
4	Is there evidence of sewage effluent discharge upstream of source/supply/system?			
5	Is there evidence of un-sewered human sanitation including septic tanks and soakaways upstream of source/supply?			
6	Is soil within vicinity of water source/supply/system regularly cultivated with waste water irrigation or sludge/slurry/manure application?			
7	Is surface run-off from agricultural activity diverted to flow into the source/supply?			
8	Has disposal of organic wastes to land occurred within vicinity of source/supply/system?			
10	Are farm wastes and/or silage stored on the ground (not in tanks or containers) within vicinity of source/supply/system?			
11	Are there waste disposal sites (including scrap yard, rubbish and hazardous waste disposal, landfill or incinerator including on-farm incineration) within vicinity of source/supply/system?			
12	Are there disposal sites for animal remains within vicinity of source/supply/system?			
13	Is there evidence of use of pesticides (including sheep dip) near source/supply/system?			
14	Is there evidence of industrial activity likely to present a contamination threat to source/supply/system?			
15	Is there forestry activity in vicinity of source/supply/system?			
16	Is there evidence of wildlife (rabbits, badgers, deer, etc.) within vicinity of source/supply?			
17	Are agricultural workers aware of the presence of drinking water supply/source/system?			
SPRINGS, WELLS AND BOREHOLES		**EVALUATION**		
		YES	**POSSIBLE**	**NO**

18	Is there evidence of poor drainage causing stagnant/standing water in vicinity of source/supply?			
19	Are there supplies or wells not in current use?			

Supply Survey

Are any of the following known to occur at the head works site in relation to the supply?

BOREHOLES		**EVALUATION**		
		YES	**POSSIBLE**	**NO**
20	Is there a suitable barrier present to prevent ingress of surface flows into the chamber (e.g. cut-off ditch lined with impermeable material, steep incline/decline such as embankments, appropriate walls, etc.)?			
21	Is there a concrete apron sloping away from borehole lining?			
22	Is there a reinforced concrete cover slab, or equivalent, in satisfactory condition with a watertight, vermin-proof inspection cover present to BS 497 (lockable, steel type or equivalent) with or without ventilation?			
23	If the headworks are below ground then is the top of the chamber less than 150 mm above ground level?			
24	Is the housing covering the headworks watertight and/or vermin proof and/or secure?			
25	Does the borehole lining (casing) extend at least 150 mm above level of floor?			
26	Is a watertight lining cap fitted?			
27	Is the housing construction in a satisfactory state-of-repair?			
WELL AND SPRING SOURCES (WITH COLLECTION CHAMBERS)		**EVALUATION**		
		YES	**POSSIBLE**	**NO**
28	Is there a suitable barrier present to prevent ingress of surface flows into the well/chamber (e.g. cut-off ditch lined with impermeable material, steep incline/decline such as embankments, appropriate walls etc.)?			
29	Is the top of the well less than 150 mm above the concrete apron or surrounding ground?			

30	Is there a reinforced concrete cover slab, or equivalent, in satisfactory condition with a watertight, vermin-proof inspection cover present to BS 497 (lockable steel type or equivalent) with or without ventilation?			
31	Is the inlet pipe fitted with a course filter or screen?			
32	Is there a stock proof fence (to BS 1722 or equivalent) at a minimum of 4 m around the source?			
33	Is there a concrete apron, a minimum of 1200 mm, sloping away from the well/chamber and in good repair?			
34	Is the well/chamber construction in a satisfactory state-of-repair?			
35	Is the overflow/washout pipe fitted with a vermin proof cap?			

Supply Survey (continued)

Are any of the following known to occur in relation to the supply?

ALL SITES		EVALUATION		
		YES	POSSIBLE	NO
37	Are Intermediate tanks (e.g. collection chamber holding tanks, break-pressure tanks) adequately protected from contamination (see 28 to 33 above)?			
38	Is the chamber/s in an unsatisfactory state-of-repair?			
39	Is the supply network constructed from material liable to fracture e.g. asbestos-concrete, clay etc.?			
40	Do junctions present in the supply network, particularly those supplying animal watering systems, have back-siphon protection fitted?			
42	If present, does the header tank within the property(s) have a vermin-proof cover?			
45	Are there noticeable changes in the level and flow of water throughout the year?			
46	Are there noticeable changes in the appearance of the water (colour, turbidity – cloudiness) after heavy rainfall or snow melt?