The impacts on human health and environment arising from the spreading of sewage sludge to land (CR/2016/23): Sewage sludge processing systems in Scotland

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James Hutton Institute

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Cover image: Nigg Waste Water Treatment Works. Image from: http://www.scottishwater.co.uk/investment-and-communities/your-community/nigg-wwtw

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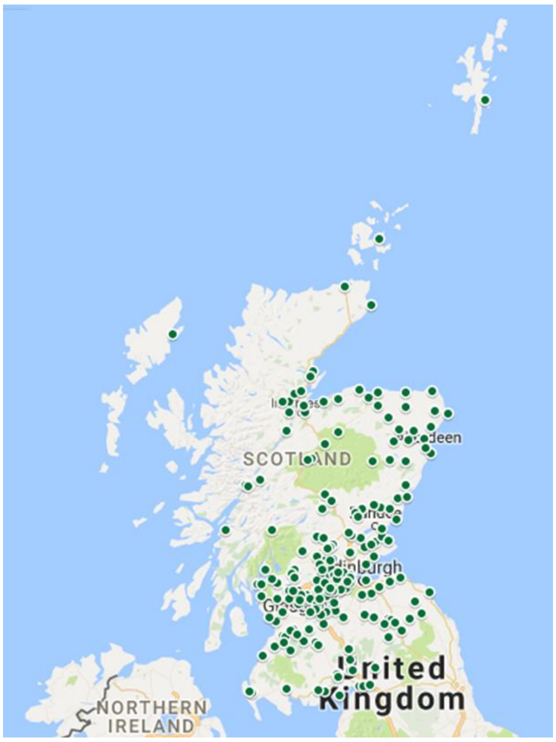
Table of Contents

1 Sludge processing in Scotland

During wastewater treatment, sludges can be generated by several processes. Incoming wastewater is first screened to remove gross physical contaminants, and then settled. The settling process gives rise to primary sludge and a clarified supernatant, which is then passed forward for secondary treatment. Secondary treatment is normally aerobic, with aerobic microorganisms consuming the nutrients in the supernatant. When these microorganisms are settled out of suspension, they constitute biological or 'activated' sludge. Both primary and biological sludges are then subjected to further treatment, which converts them to biosolids suitable for use in markets that include: agriculture, land restoration and thermal energy recovery.

Sludges can be processed on the wastewater treatment works where they arise ('indigenous' sludges) or be transported to another sludge treatment centre for processing (where they become 'imported' sludges). The extent of transfer of sludges between sites will depend on inherent treatment capacities, as well as planned or unscheduled maintenance. Thus, some wastewater treatment works will always plan to send their sludges to a particular sludge treatment centre, whilst others will send to a convenient treatment centre that has capacity at that time. This web of logistical connections makes it difficult to track biosolids back through the treatment process to their original point of origin in any given wastewater catchment. Some examples of these connections are given in
Table 1-3. A map of waste water treatment facilities in Scotland (treating loads greater than a population equivalent (pe) of 2,000) is provided in Figure 1-1.

Figure 1-1 Scottish Water waste water treatment facilities treating loads greater than 2,000pe (data from https://www.eea.europa.eu/data-and-maps/data/waterbase-uwwtd-urban-waste-water-treatment-directive-5)



Our focus in this section is on the sludge treatment centres themselves – the processes they employ to treat sludges (whether indigenous or imported), and the quantities of biosolids that are then despatched for agricultural use. Different sludge treatment processes provide different opportunities for hazard management – but by taking the process from the point at which sludges are treated (rather than the point at which wastewaters are treated) means that some hazard management options are omitted. For example, Scottish sludges are not usually composted or subjected to other active aerobic treatments – hazards present in wastewater that require aerobic processing to degrade must therefore be addressed during wastewater (rather than sludge) treatment.

Sludge treatment in Scotland is split between sites that are owned and operated by Scottish Water (the Scottish Water 'core' sites) and sites that are owned and operated by third parties (the Scottish Water 'PPP' or Public-Private-Partnership sites). There are 32 core sites (Figure 1-2 and Table 1-1) and 21 PPP sites (Figure 1-3). Not all sludge treatment centres produce sludges ready for their final market destinations – for example, only 14 of the PPP centres despatched sludges to market in 2017 (Table 1-2), whilst the remainder despatched sludge to other sites for further processing (

Table 1-3). The majority of sludges destined for use in agriculture are produced by the PPP sites (Figure 1-5).

Figure 1-2 Scottish Water core sludge treatment centres in Scotland

Table 1-1 Scottish Water 'core' sludge treatment centres and output tonnage in 2016 (tonnes dry solids or tds). Data from Scottish Water

Sludge treatment centre	Sludge destination	Output (tds)
Allanfearn	Agriculture	1,671
Aviemore	PPP site	127
Balivanich	Land restoration	52
Brechin	PPP site	596
Broadford	PPP site	87
Cumnock	Agriculture	491
Cupar	Land restoration	368
Dalderse	Agriculture and Land restoration	790
Dalmuir	Land restoration	3,033
Dornoch	PPP site	262
Dunfermline	Agriculture and Land restoration	3,216
Galashiels	Agriculture	1,155

Sludge treatment centre	Sludge destination	Output (tds)
Girvan	Agriculture	565
Hawick	Agriculture	149
Huntly	PPP site	147
Invergordon	Agriculture	730
Kinneil Kerse	Agriculture	3,163
Kirkcaldy	Land restoration	770
Lochgilphead	Land restoration	87
Nairn	PPP site	189
Oban	Land restoration	299
Orkney	Agriculture	295
Perth	Agriculture	4,651
Shetland	Landfill	363
Shieldhall	Land restoration	1,361
St Andrews	Land restoration	447
Stirling	Agriculture and Land restoration	449
Stornoway	Agriculture	115
Thurso	Agriculture	561
Troqueer	Land restoration	1,752
Ullapool	PPP site	24
Wick	PPP site	141

Figure 1-3 Scottish Water PPP sludge treatment centres

Table 1-2 Scottish Water PPP sludge treatment centres and output tonnage in 2016 (tonnes dry solids or tds). Data from https://www.watercommission.co.uk

Sludge treatment centre	Sludge destination	Output (tds)
Inverness	Agriculture	2,661
Hatton	Agriculture	5,481
Nigg	Agriculture	13,140
Persley	Land restoration	159
Peterhead	Land restoration	267
Fraserburgh	Land restoration	58
Lossiemouth	Agriculture	3,102
Seafield	Agriculture and Land restoration	20,318
Newbridge	Land restoration	2,306
East Calder	Exported to other sites	
Levenmouth	Agriculture and Incineration	3,373
Meadowhead	Agriculture, Land Restoration and Incineration	8,985

Sludge treatment centre	Sludge destination	Output (tds)
Dalmuir	Land restoration	2,724
Daldowie	Agriculture, Land Restoration and Incineration	47,332

Table 1-3 Sources of sludge for PPP treatment / processing centres. https://www.watercommission.co.uk/UserFiles/Documents/Commentary_2.pdf

PPP site	Sources of sludge
Inverness	Indigenous sludge, imports from Fort William, plus Scottish Water imports
Hatton	Indigenous sludge plus Scottish Water imports
Nigg	Indigenous sludge, imports from Persley, Peterhead, Fraserburgh, plus Scottish Water imports
Lossiemouth	Indigenous sludge, imports from Buckie, Banff/Macduff, plus Scottish Water imports
Seafield	Indigenous sludge, occasional imports from Newbridge, East Calder, Blackburn, Whitburn, plus Scottish Water imports
Newbridge	Indigenous sludge, imports from East Calder, Blackburn, Whitburn, plus Scottish Water imports
Levenmouth	Indigenous sludge, plus Scottish Water imports
Daldowie	Sludge from Dalmuir and Scottish Water WWTW (Daldowie, Shieldhall, Paisley, Dalmarnock and Erskine) by pipeline, and from Scottish Water tankered imports
Meadowhead	Indigenous sludge, plus imports from Stevenston and Inverclyde

Figure 1-4 Waste Water Treatment Works (>2,000pe) (green), Scottish Water STCs (blue) and PPP STCs (purple)

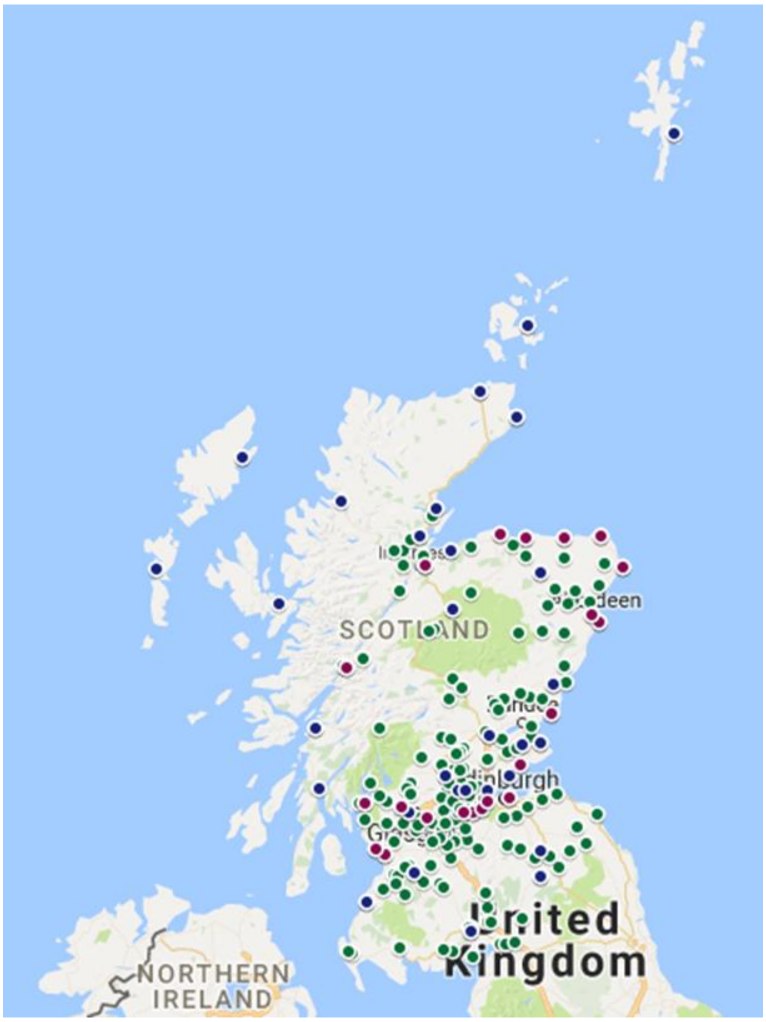
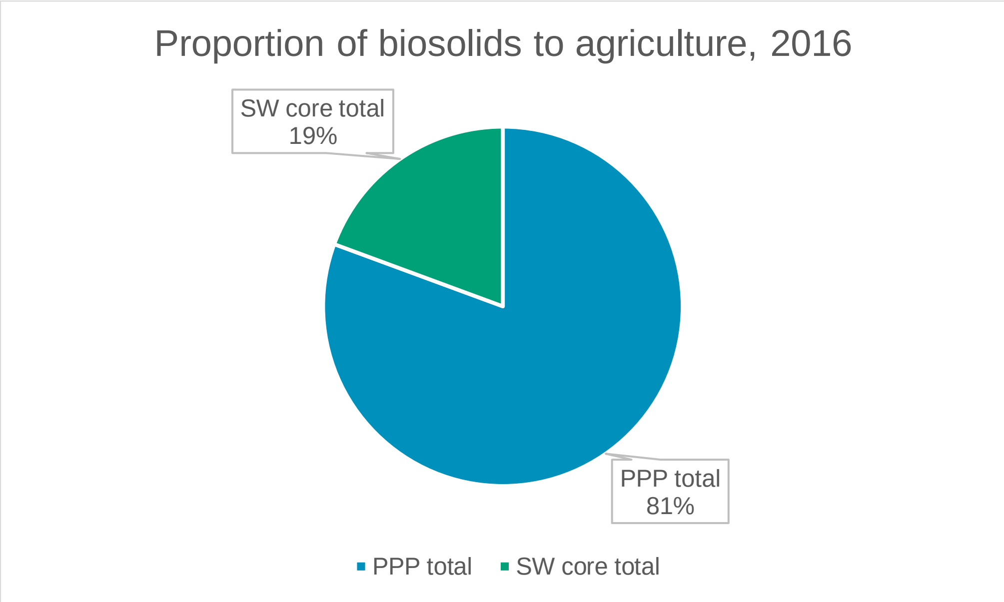


Figure 1-5 Proportions of biosolids to agriculture from Scottish Water core and PPP sites in 2016 (by percentage weight in dry tonnes). Data from Scottish Water and https://www.watercommission.co.uk



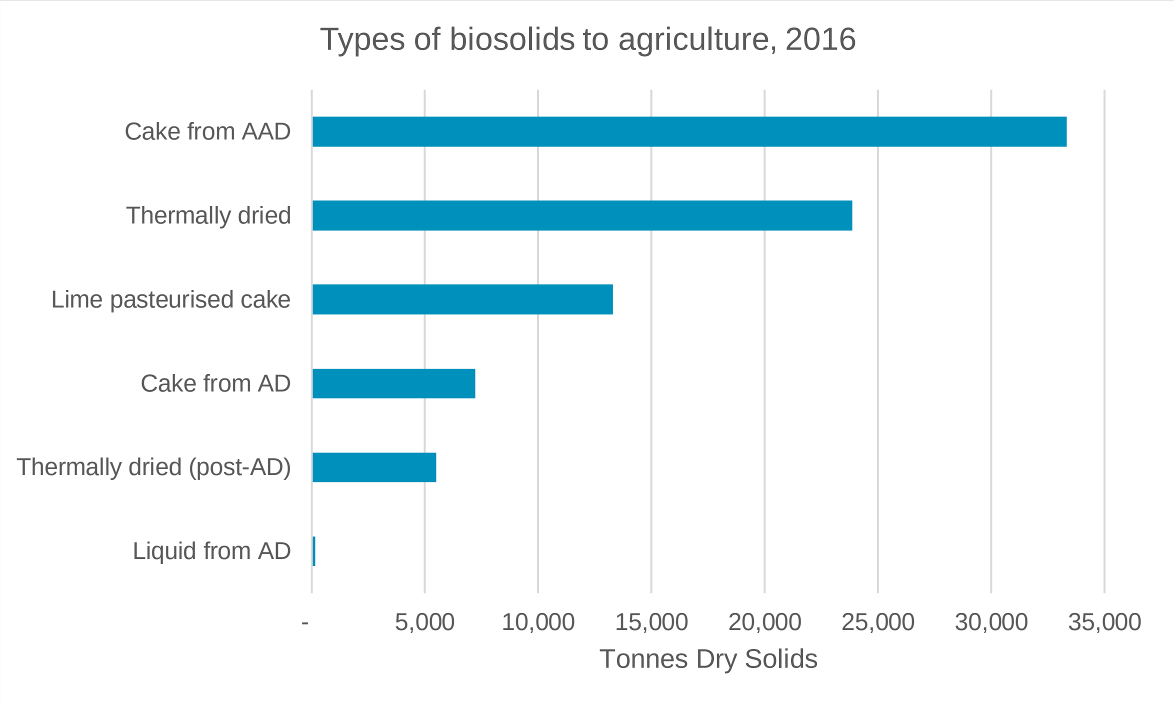
1.1 Types of treated sludge applied to agricultural land in Scotland

Broadly, six different sludge treatment process are undertaken across the fleet of Scottish Water core and PPP sites:

1. Advanced Anaerobic Digestion, followed by de-watering to produce biosolids cake with dry matter of around 30%;
2. Drying (without prior anaerobic digestion or other stabilisation), to produce biosolids pellets with a dry matter of around 95%;
3. Liming, in which sludges are mixed with lime or quicklime before or after de-watering, to produce biosolids cake with dry matter of around 40%;
4. Conventional Anaerobic Digestion, followed by de-watering to produce biosolids cake with dry matter of around 25%;
5. Conventional Anaerobic Digestion, followed by de-watering and then drying and pelletisation to produce biosolids pellets with a dry matter of around 95%;
6. Conventional Anaerobic Digestion, with the whole (liquid) sludge applied to land at a dry matter of around 4%.

The relative quantities of different types of treated sludge applied to agricultural land are presented in Figure 1-6. The most significant tonnage is in the form of cake produced by Advanced Anaerobic Digestion, followed by thermally dried sludge pellets and then lime pasteurised cake. From discussions with industry experts, we understand that no liquid sludges are now applied to land in Scotland.

Figure 1-6 Types and quantities of biosolids (tonnes dry solids) supplied for agricultural use in 2016. Data from Scottish Water and https://www.watercommission.co.uk



Within some of these categories (for example, liming), there are site-specific differences relating to the points and form at which lime is introduced to the process – however, the aim of lime treatment (as with all other sludge treatments) is to manage pathogen loading in the sludge. Specifically, the aim is to produce biosolids that can either be considered Conventionally or Enhanced-treated, in line with the requirements of the Safe Sludge Matrix (Section 2.2.1):

1. Conventionally Treated = 2$\log_{10}$ (or 100-fold) kill of *E. coli*;
2. Enhanced Treated = 6$\log_{10}$ (or 1,000,000-fold) kill of *E. coli* and no *Salmonella* present

The terminology used in reporting sludge treatment data in Scotland lists markets that include 'Farmland Conventional' and 'Farmland Advanced' ((for example, see https://www.watercommission.co.uk/view_2016-17.aspx) (Figure 1-13)). We have assumed that 'Farmland Advanced' means biosolids that comply with the Safe Sludge Matrix category 'Enhanced Treated', and have set out our wider interpretation of sludge treatment efficacy in Table 1-4.

Table 1-4 Relationship between sludge treatment processes, market reporting and Safe Sludge Matrix treatment categories for biosolids

Sludge treatment process	Conventional or Advanced?	Safe Sludge Matrix equivalent
Advanced AD and de-watering	Advanced	Enhanced Treated

Drying only	Advanced	Enhanced Treated
Liming	Advanced	Enhanced Treated
AD and de-watering	Conventional	Conventionally Treated
AD and drying	Advanced	Enhanced Treated
AD	Conventional	Conventionally Treated

1.2 Sludge treatment approaches

As set out above, six different types of treatment system are applied to sludges destined for application to agricultural land in Scotland. Each of these systems comprise combinations of different tertiary (sludge) processing techniques, each of which has the potential to impact differently on different hazards present in the sludge. The key objective of tertiary treatment is compliance with the Safe Sludge Matrix – delivering consistent impact on indicator pathogens – but changes in pH and temperature may also impact on other hazards of interest. This potential is considered in Section 0, whilst the different processing techniques as listed in Table 1-4 are illustrated in Figure 1-7 to Figure 1-11, below.

1.2.1 Primary and Secondary Treatments

Primary treatment usually comprises clarification of the raw effluent, whereby the incoming wastewater is held in a quiescent basin – allowing heavy solids to settle to the bottom while oil, grease and lighter solids float to the surface. This principal stage is the mainstay of sludge production in wastewater treatment plants. The supernatant liquor is passed forwards for secondary treatment, whilst the settled sludge (‘primary sludge’) is collected and passed forwards for further treatment.

Secondary treatments are employed to reduce biological and suspended matter in the liquor. This is achieved using the indigenous waterborne microorganisms to biologically degrade the organic material in a well aerated liquor. Such treatments produce a final effluent (normally suitable for discharge to water body, following any final polishing) and a biological sludge (‘Activated Sludge’). Surplus Activated Sludge is collected and passed forwards for tertiary treatment, along with primary sludges.

1.2.2 Tertiary treatments

Anaerobic Digestion processes are commonly applied to sewage sludges, since they serve to break down organic matter whilst simultaneously generating renewable energy in the form of biogas (~60% CH_4 and 40% CO_2). AD processes are usually mesophilic, operating at temperatures of around 35°C – and heat is normally required to maintain digester contents at optimum temperatures. Mesophilic Anaerobic Digestion (MAD) can deliver a $2\log_{10}$ reduction in *E. coli* (Mara & Horan, 2003) or Conventionally Treated biosolids.

Advanced Anaerobic Digestion systems incorporate pre-treatment techniques ahead of MAD. In Scotland, the most common pre-treatment is Thermal Hydrolysis or THP. THP was originally designed as a method to improve the dewaterability and degradability of sludge. However, when used as a pre-treatment to anaerobic digestion, the rate of biogas production and the efficiency of the digestion process are also improved. Sludge is generally heated to a temperature between 130 – 200°C for about 30 minutes in a pressure vessel. The sudden release of pressure results in cell lysis, releasing intracellular contents and reducing sludge viscosity. This improves the bioavailability of the sludge, enhancing the performance of anaerobic digestion by allowing biogas to be produced more rapidly than without THP. This can, in turn, allow digestion vessels to be smaller and/or retention times to be decreased.

Since 1995, the Cambi process has been the major THP technology used in AAD. Sludges are first dewatered to 17% dry solids before being steam heated under pressure to between 150 and 180°C. These conditions are held for up to 30 minutes before the treated sludge is flashed (rapidly de-pressurised) into a flash tank. Veolia also supply THP systems, with different configurations that can treat sludges either in batches, or continuously (Hii et al., 2017). AAD systems incorporating THP can reduce *E. coli* populations to undetectable levels (Martinez & Lema, 2017) and as such are capable of delivering the $6\log_{10}$ reductions required for Enhanced Treated biosolids.

Thermal Drying can be applied to raw sludges or those that have undergone preliminary treatment (such as MAD or AAD). The attraction of thermal drying is that it reduces sludge volumes very significantly (thereby reducing the costs of downstream haulage and land application). However, this energy intensive process normally requires heat recovery from other plant processes for it to be economically viable, and benefits from efficient initial dewatering of sludges. The temperatures achieved during drying (~450°C) are sufficient to meet the pathogen reduction requirements of Enhanced Treated biosolids (Mara & Horan, 2003). The energy requirements for thermal drying mean that this technique is normally applied to sludges intended for subsequent incineration with energy recovery[1]. However, as is evident from Figure 1-6, dried sludges comprise a significant proportion of biosolids applied to agricultural land in Scotland.

Liming can raise the temperature of sludges to over 55°C, and pH to more than 12. When held at such elevated pH for more than two hours, this technique is capable of delivering Enhanced Treated biosolids (Mara & Horan, 2003). Lime can be added to sludges in various chemical and physical forms, with the efficacy of mixing having a direct relationship to odour potential from the treated sludge (Mangus et al, 2006).

[1] https://www.scottishpower.com/userfiles/file/Daldowie%20Site-Information-2014.pdf

Figure 1-7 Overview of waste water and sludge treatment, including Advanced Anaerobic Digestion (Thermal Hydrolysis-AD) and de-watering

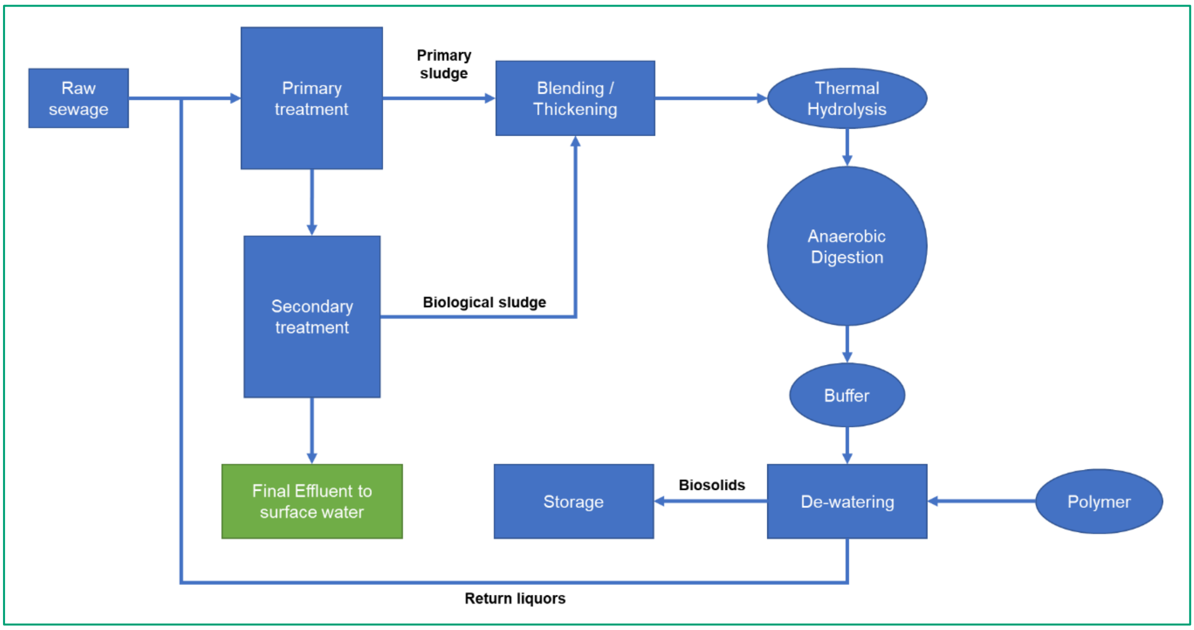


Figure 1-8 Overview of waste water and sludge treatment, including drying and granulation

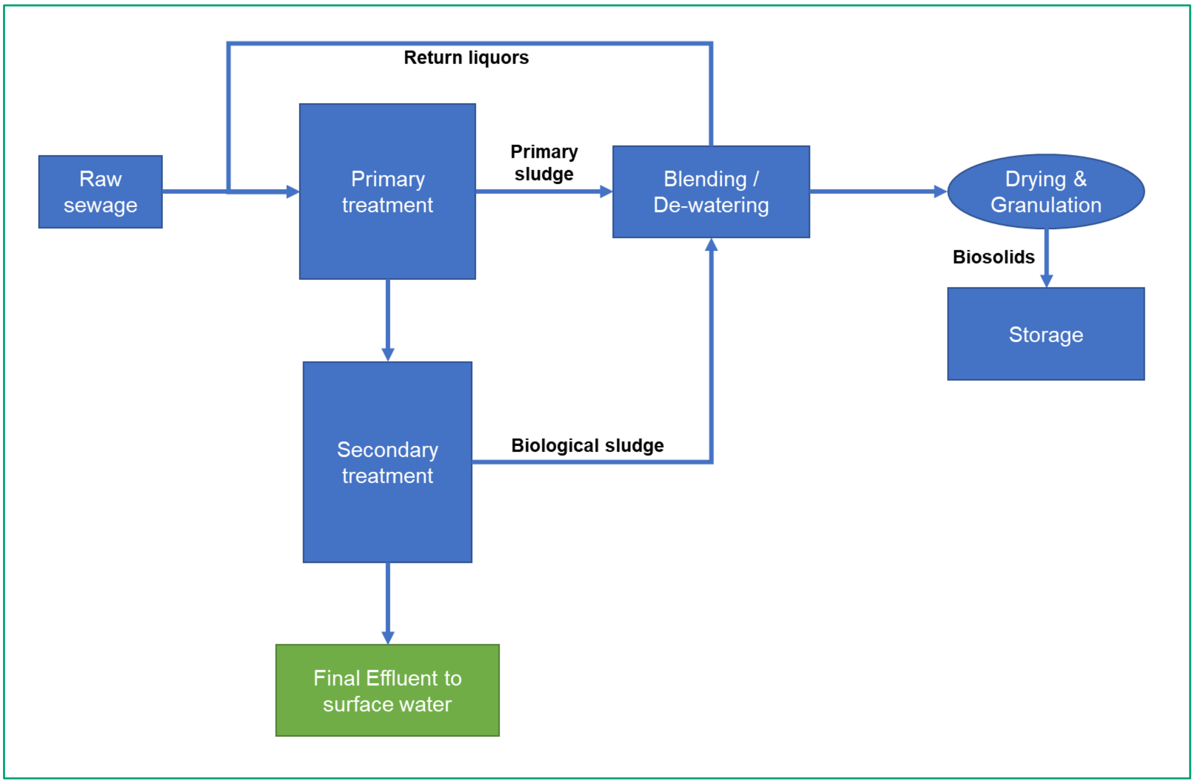


Figure 1-9 Overview of waste water and sludge treatment, including lime pasteurisation

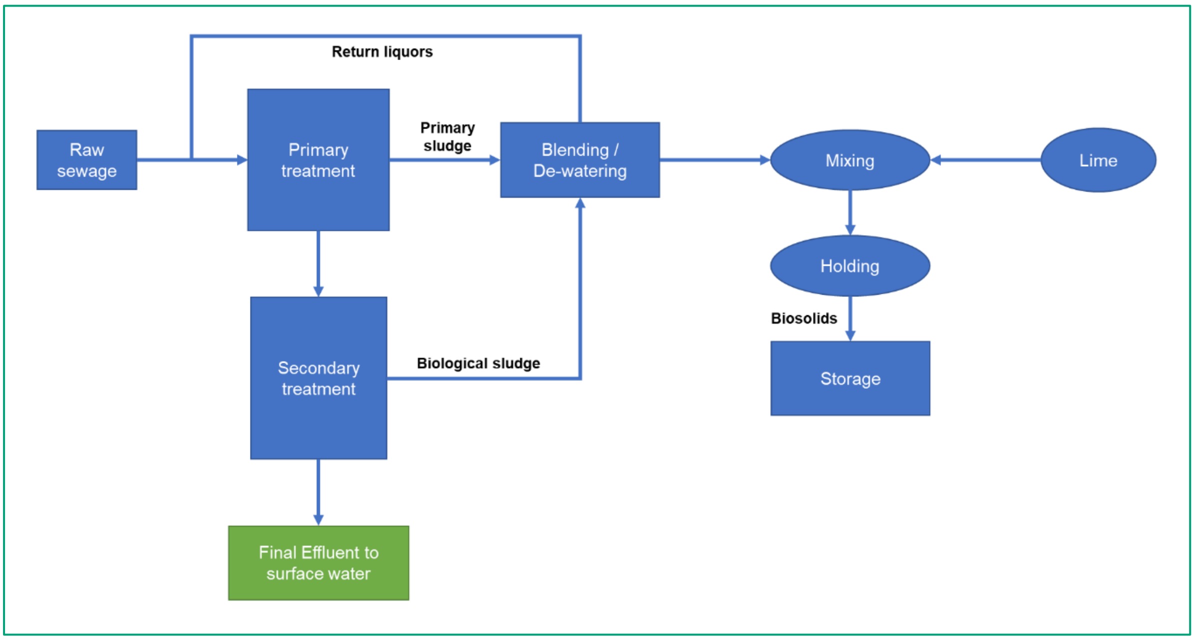


Figure 1-10 Overview of waste water and sludge treatment, including conventional Anaerobic Digestion and de-watering

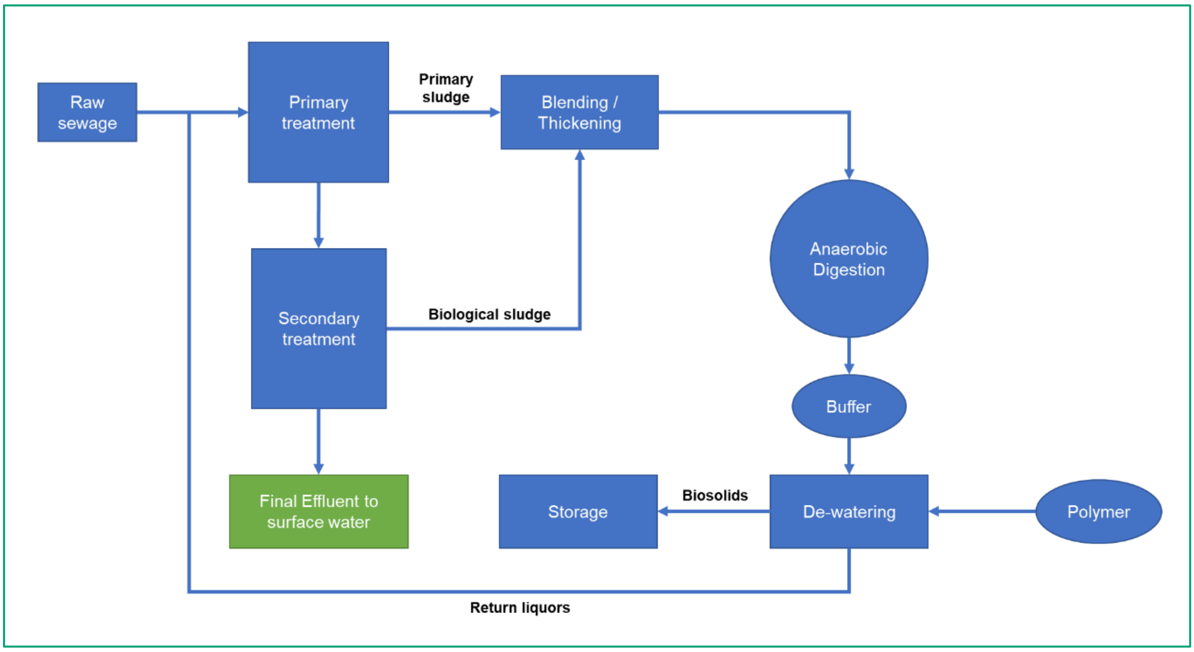
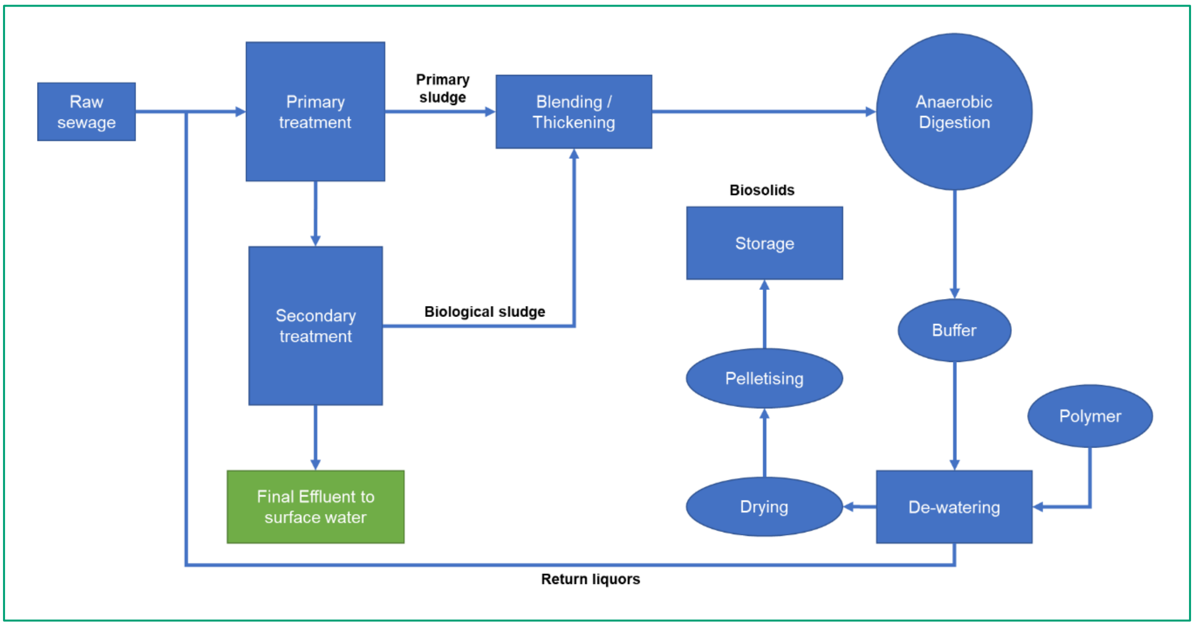


Figure 1-11 Overview of waste water and sludge treatment, including conventional Anaerobic Digestion, de-watering, drying and pelletising



1.2.3 Types of biosolids supplied for agricultural use in Scotland

The proportion of biosolids applied to agricultural land in Scotland has remained relatively consistent over the past decade (Figure 1-12), ranging from 52,381 tonnes (dry solids) in 2007 to 45,646 tonnes (dry solids) in 2017. Of this tonnage, the significant majority is categorised as Enhanced Treated (Table 1-5 and Figure 1-13), with small contributions of Conventionally Treated sludges from both PPP and Scottish Water core sites. Enhanced status provides biosolids with the greatest degree of flexibility in terms of access to potential agricultural markets.

Table 1-5 Biosolids end points in Scotland during 2017

Market / biosolids end point	Quantity (tonnes dry solids)	Proportion (%)
Agriculture (Conventionally Treated)	3,279	3.2
Agriculture (Enhanced Treated)	42,367	41
Landfill	393	0.4
Incinerated	37,275	36
Land reclamation	19,617	19
Other	242	0.2
Total	**103,173**	**100**

Figure 1-12 Markets for sludges from all sludge treatment / processing facilities in Scotland. Data from Scottish Water

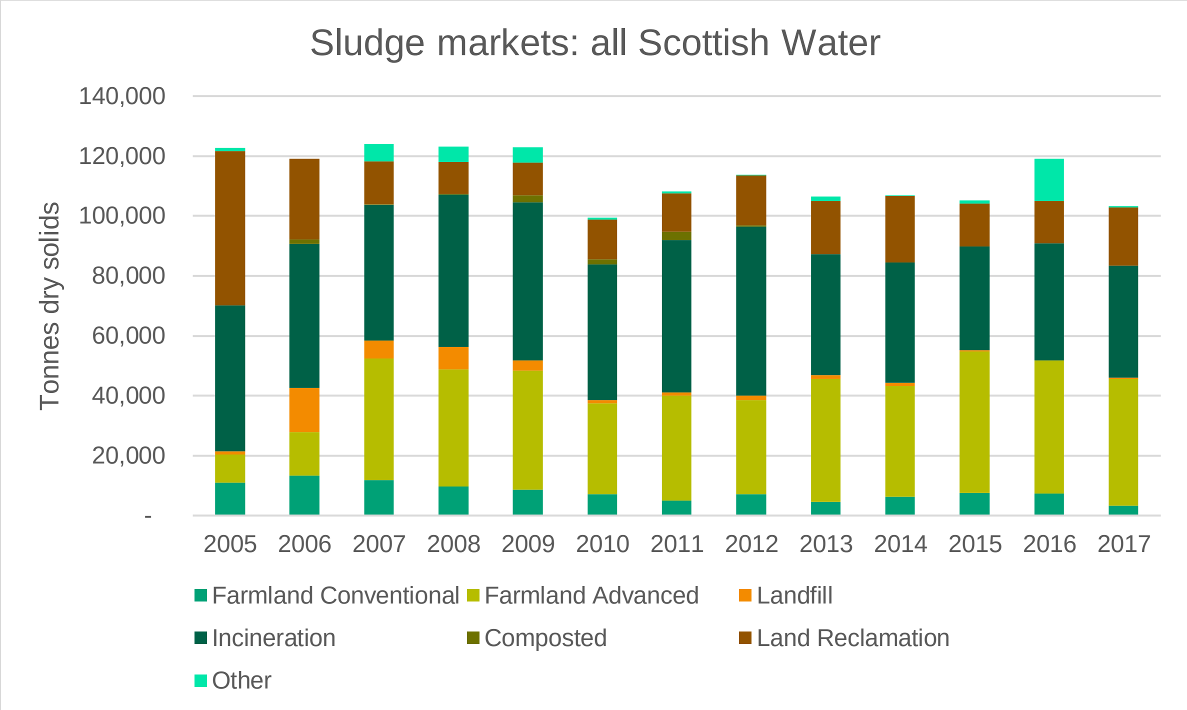
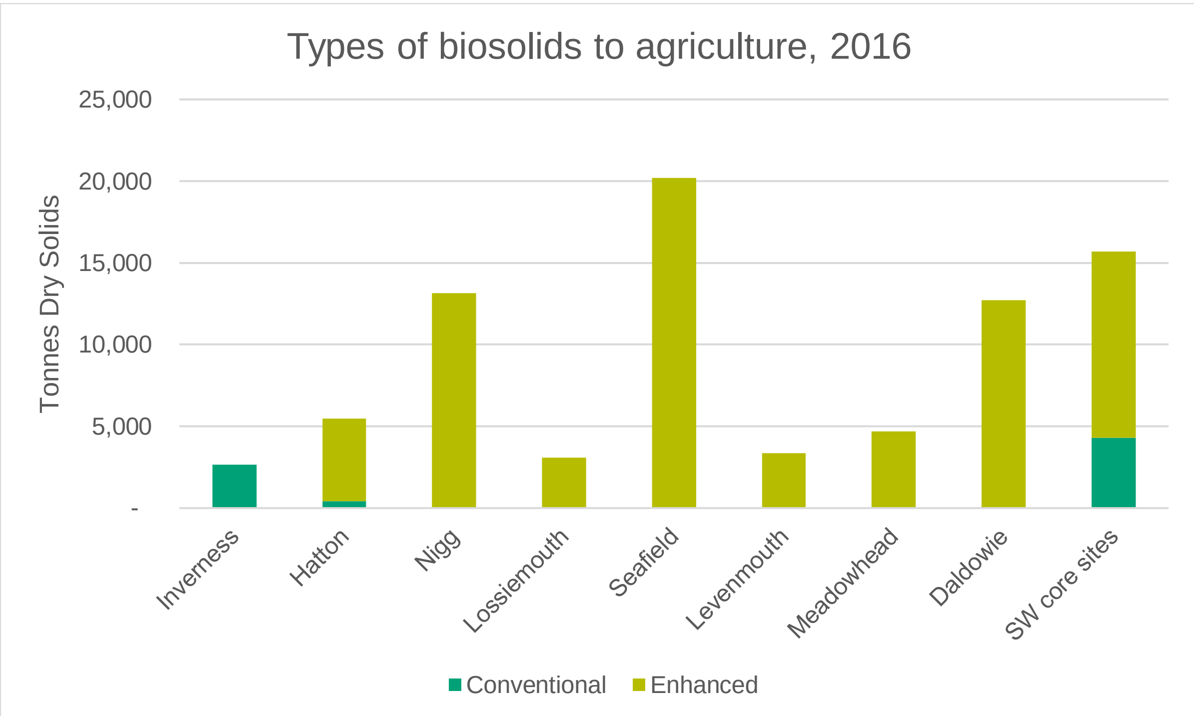


Figure 1-13 Conventionally and Enhanced Treated biosolids supplied to agriculture in 2016. Data from Scottish Water and https://www.watercommission.co.uk



1.2.4 Options for hazard management during processing

As noted above, biosolids supplied for agricultural use arise from one of five different treatment processes (six if liquid sludges are considered). The relative quantities of sludge from these different processes are listed in Table 1-6.

Table 1-6 Tonnages of sludge (dry solids) supplied for agricultural use in 2016. Data from Scottish Water and https://www.watercommission.co.uk

Plant	Treatment type	Tonnage to agriculture
Nigg	THP-AD and dewatering	13,140
Seafield	THP-AD and dewatering	20,189
Daldowie	No digestion, cake dried to pellets	12,717
Levenmouth	No digestion, cake dried to pellets	3,350
Lossiemouth	No digestion, cake dried to pellets	3,102
Meadowhead	No digestion, cake dried to pellets	4,687
Dunfermline*	Lime Pasteurised Cake	3,216
Girvan	Lime Pasteurised Cake	565
Invergordon	Lime Pasteurised Cake	730
Kinneil Kerse	Lime Pasteurised Cake	3,163
Orkney	Lime Pasteurised Cake	295
Perth	Lime Pasteurised Cake	4,651
Stornoway	Lime Pasteurised Cake	115
Thurso	Lime Pasteurised Cake	561
Allanfearn	AD and dewatering	1,671
Cumnock	AD and dewatering	491
Dalderse*	AD and dewatering	790
Galashiels	AD and dewatering	1,155
Inverness	AD and dewatering	2,661
Stirling*	AD and dewatering	449
Hatton	AD, cake dried to pellets	5,481
Hawick+	AD (no dewatering)	149

***Note that for these sites, data do not discriminate between tonnages to agriculture and land restoration. For the purposes of reporting, we have assumed that the whole tonnage from each site is supplied to agriculture**

+The output from Hawick is liquid sludge. It is our understanding that no liquid sludge is now applied to agricultural land in Scotland (*pers comm* Debbie Neely, Entrust Environmental)

Whilst sludge quality is normally focussed on pathogen management (and classification according to Enhanced or Conventionally Treated), the different treatment processes may afford different opportunities for managing other hazards known to be present in sludges. These processes can be simplified to:

1. Elevated pressure and temperature (thermal hydrolysis);
2. Elevated temperature (drying);
3. Elevated pH (liming); and
4. Anaerobic Digestion.

Of these processes, it is possibly anaerobic digestion that has received most attention as a ‘hazard attenuation’ step in sludge treatment, with various authors having previously considered the impact of AD on hazards that include (for example) pharmaceutical and personal care products (PPCPs). Carballa et al (2007) report varying degrees of reduction through anaerobic digestion on concentrations of compounds that included galaxolide, tonalide, diazepam, ibuprofen, diclofenac and estrone. They highlighted a requirement for initial adaptation or acclimatisation of digester biology to address these compounds. Samaras et al (2003) determined concentrations of a range of PPCP compounds in sludges before and after anaerobic digestion, demonstrating removal rates of more than 80% for ibuprofen and naproxen, but lower rates for endocrine disrupting compounds such as nonylphenol monoethoxylate. Narumiya et al (2013) examined the fate and removal of 48 PPCPs during anaerobic digestion of sewage sludge at full-scale sewage treatment plants, showing that sulfamethoxazole and trimethoprim were almost completely degraded (>90%); triclosan, triclocarban, and ofloxacin were moderately degraded (around 30–50%); while carbamazepine was not eliminated.

Other sludge treatment processes have received less attention, although Malmborg & Magnér (2015) examined the fate of pharmaceutical residues in sludge treatment during AD in conjunction with either pasteurization, thermal hydrolysis, advanced oxidation, or ammonia treatment. Overall, they found that AD was capable of delivering 30% reductions in concentration of a number of spiked PPCP compounds – but that it was only through the additional use of thermal hydrolysis that estrogenic compounds were removed (estrone, 17β-estradiol and 17α-ethinylestradiol).

The impacts of these processes on hazards of particular interest are considered in Section 0.

Note that (as described above) data on sludge processing omit upstream processes by which the sludges were derived, which typically include the following approaches, each of which may be capable of attenuating certain hazards in the incoming raw sewage:

- Screening
- Aerobic treatment (as applied to primary effluent, generating activated sludge that is then processed; primary sludges are not subjected to this treatment – meaning that hazards amendable to aerobic degradation may not so degrade if partitioned to sludge during initial settlement / clarification)

2 Regulatory and best practice approaches to sludge treatment, haulage, storage and use in agriculture

As described above, the processes of waste water and sludge treatment can take place on the same site – or can be separated, with sludges transported elsewhere for treatment. Even where both streams are treated on the same site, the objectives of the treatments differ between substrates:

1. Waste water must be sufficiently treated to reach standards that allow it to be discharged into surface waters without undue harm. Standards commonly include limits on suspended solids, biochemical oxygen demand (BOD) and phosphorus concentration; and
2. Sludges must be sufficiently treated to reach standards that allow them to be used in thermal energy recovery (incineration) or land-based markets – principally agriculture. Standards applied to sludges intended for agricultural use (as 'biosolids') include limits on indicator pathogens and monitoring of potentially toxic element concentrations.

This separation of objectives means that (for example) approaches that encourage hazards to partition to sludges (thereby improving the quality of the treated waste water) can impact negatively on the quality and usability of the sludges. Whilst the latter are the focus of this report, the relationships between sludge treatment (and treatability) and waste water treatment should be considered in any wider view of hazard management options.

This section focusses on sludge treatment, haulage, storage and use in agriculture – from the perspectives of regulatory requirements, good practice and the Biosolids Assurance Scheme.

2.1 Regulatory requirements

2.1.1 Sludge treatment

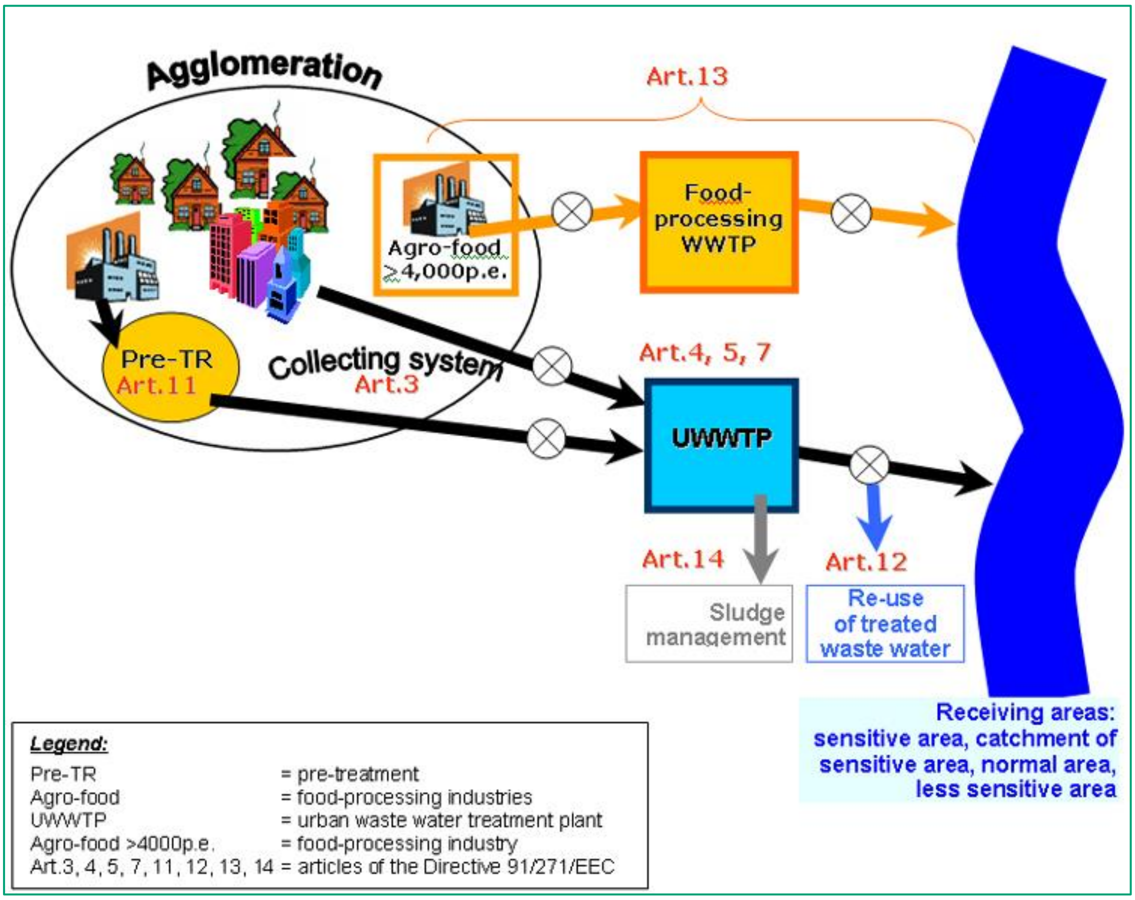
Hazards addressed by regulation	How they are addressed
In principle, the Sludge Directive captures all hazards relevant to 'health'. Only PTE limits in receiving soils are prescribed	Limits on heavy metal concentrations in soils to which biosolids are applied
Various, depending upon the nature of sewer catchment and sensitivity of water body receiving the treated waters. pH, COD, suspended solids, phosphorus and nitrogen are commonly managed	Limits are placed on trade effluents discharged into the sewer catchment Limits are placed on final effluents discharged to receiving water bodies

The process of waste water (or 'urban waste water') treatment normally falls under the requirements of European Council Directive 91/271/EEC. Its objective is to protect the environment from the adverse effects of urban waste water discharges and discharges from certain industrial sectors. It covers the collection, treatment and discharge of:

- Domestic waste water
- Mixtures of waste water
- Waste water from certain industrial sectors

The relationship between these types of waste water and the scope of the Directive is illustrated in Figure 2-1. Article 14 includes a requirement that sludge arising from waste water treatment *shall be re-used whenever appropriate,* and that sludge *Disposal routes shall minimize the adverse effects on the environment* (EC, 2017). No specific sludge treatments are prescribed by this legislation.

Figure 2-1 The scope of the Urban Waste Water Treatment Directive. Image from: http://ec.europa.eu/environment/water/water-urbanwaste/



If urban waste water treatment processes handle only indigenous material, then they are not normally covered by the requirements of the Waste Management Licensing (Scotland) Regulations. However, processes that import controlled wastes such as sludges, septic tank sludge or screenings from outwith the curtilage of the works are required to hold a Waste Management Licence (WML).

The requirements of a WML will be specific to the individual works, but would normally include odour management conditions such as: 'Waste operations shall be carried out so that offensive odours from the site as perceived by an authorised SEPA officer, do not become detectable beyond the boundaries of the site'. Depending on the scale of activity, a WWT facility may import and treat sludges under a Paragraph 10 Exemption, rather than a full WML (Quinn et al., 2016). This covers 'Reception and treatment of specified waste at a Water Treatment Works'. Specified wastes include 'Sludges from treatment of urban waste water', and there is an upper limit of 100,000m^3 of (combined, specified) wastes in any 12 month period. The Exemption requires that wastes are 'managed without endangering human health and without using processes or methods which could harm the environment and in particular, without:

(a) Risk to water, air, soil, plants or animals; or

(b) Causing nuisance through noise or odours; or
(c) Adversely affecting the countryside or places of special interest

Limits are applied to treated water that is discharged back to the environment, as set out in Table 2-1.

Table 2-1 Requirements for discharges from urban waste water treatment plants. Values for concentration or the percentage of reduction apply (HMSO, 1994)

Parameters	Concentration	Minimum percentage of reduction
Biochemical Oxygen Demand (BOD_5 at 20°C) without nitrification	25 mg/l O_2	70-90
Chemical Oxygen Demand	125mg/l O_2	75

Where treated waste water is discharged into a sensitive area, then limits are placed on the phosphorus and nitrogen content of the treated water **Table** 2-2. A map of sensitive areas in Scotland is provided in Appendix 1.

Table 2-2 Requirements for discharges from urban waste water treatment plants into sensitive areas, which vary according to WWTW load (in population equivalent or p.e.). Values for concentration or the percentage of reduction apply (HMSO, 1994)

Parameters	Concentration	Minimum percentage of reduction
Total phosphorus	2mg/l P (WWTW with loads equivalent to between 10,000 and 100,000 p.e.) 1mg/l P (WWTW with loads equivalent to more than 100,000 p.e.	80
Total nitrogen	15mg/l P (WWTW with loads equivalent to between 10,000 and 100,000 p.e.) 10mg/l P (WWTW with loads equivalent to more than 100,000 p.e.	70-80

Trade connections to the sewer network also require consent (under the terms of the Sewerage (Scotland) Act 1968, as amended) (HMSO, 1968). This makes provision for limits to be placed on characteristics of the effluent that are specific to the nature of that effluent; limits for discharges to sewer from a distillery may be very different to limits for discharges to sewer from a metal plating works.

This regulatory environment is intended to ensure that treated waste waters are of appropriate quality when discharged to the environment. They do not focus on hazards directly relevant to sludge quality. Indeed, some treatments for waste waters – such as dosing with iron or aluminium salts to precipitate phosphorus – can directly influence the quality of sewage sludge prior to treatment, and their inherent treatability. Such influences are out of scope for this report.

The European Sewage Sludge Directive (86/278/EEC) seeks to encourage the use of sewage sludge in agriculture. It prohibits the use of untreated sludges (except where injected or otherwise incorporated into soil) and defines the treatment of sludge as "biological, chemical or heat treatment, long-term storage or any other appropriate process so as significantly to reduce its fermentability and the health hazards resulting from its use". The Directive does not prescribe treatments (EC, 2016).

2.1.2 Sludge transport

Hazards addressed by regulation	How they are addressed
No hazards specific to sludge are addressed by regulation – although loss of containment / spillage would constitute a breach of Duty of Care	Sludge hauliers should register with SEPA as professional transporters of waste

When intended for application to agricultural land under the requirements of the Sludge (Use in Agriculture) Regulations (1989), biosolids are not considered a controlled waste, and need not therefore be transported by a registered waste carrier. However, the Biosolids Assurance Scheme (see Section 0) requires that biosolids are transported as though they are wastes. The requirement to register as a professional transporter of waste is not prescriptive as to the manner of transportation, although licensed waste carriers are subject to Duty of Care (Scottish Government, 2012). Amongst other requirements, this states that all waste holders must act to keep waste safe against:

- Spillages from corrosion or wear and tear of containers;
- accidental spilling or leaking or inadvertent leaching from waste unprotected from rainfall;
- accident or weather breaking contained waste open and allowing it to escape;
- waste blowing away or falling while stored or transported;

- scavenging of waste by vandals, thieves or animals.

It also requires that handling of wastes avoid harm or pollution.

2.1.3 Sludge storage

Hazards addressed by regulation	How they are addressed
Odour nuisance	Must not be created as a result of storing biosolids where they are to be used under a Paragraph 8(1) Exemption from Waste Management Licensing
Nutrients	Under General Binding Rules, dewatered sewage sludges must be stored in such a way that ingress of water or runoff are prevented; Field stores of dewatered biosolids must be applied to land within six months of deposition in the store
Nutrients	Sludge stockpiles must be situated at specified distances from water bodies, to reduce the potential for contamination by nutrients during storage. Within Nitrate Vulnerable Zones, long term biosolids storage areas must have an impermeable surface and must either have a facility to collect, store and recover runoff or the biosolids must be covered with waterproof covering.

The storage of biosolids where they are intended to be used (under the Sludge (Use in Agriculture) Regulations, 1989) is authorised under an exemption to waste management licensing – meaning that SEPA must be notified. Various conditions attach to this (‘Paragraph 8(1)’) exemption (SEPA, 2011):

- the sludge is stored at the place where it is to be used;
- the sludge is stored at a distance of not less than—
    - 10 metres from any inland or coastal waters;
    - 50 metres from any well, borehole or similar work sunk into underground strata for the purpose of any water supply other than a domestic water supply; and
    - 250 metres from any well, borehole or similar work sunk into under ground strata for the purpose of a domestic water supply;
- no sludge is stored for longer than 6 months

It should be noted that – although such storage should be ‘secure’ – there is no minimum distance from householders or other human receptor within which such stores can be located.

Dewatered sewage sludges are subject to General Binding Rules (GBR) under The Water Environment (Controlled Activities) (Scotland) Regulations 2011 (as amended). These materials must be stored:

- in such a way that they are securely contained so that any escape or runoff is prevented; or
- in a heap which is protected from the ingress of water

Furthermore, if dewatered sewage sludge is stored in a heap in field, it must be applied to land within 6 months of the commencement of the storage.

As with other ‘organic manures’, biosolids are captured by the requirements of the Nitrates Directive when applied within designated Nitrate Vulnerable Zones (EEC, 1991). Within Nitrate Vulnerable Zones, long term biosolids storage areas must have an impermeable surface and must either have a facility to collect, store and recover runoff or the biosolids must be covered with waterproof covering.

2.1.4 Sludge use

Hazards addressed by regulation	How they are addressed
In principle, all hazards that might impact on the 'quality of the soil and of the surface and ground water'. In practice, only potentially toxic elements are explicitly (if indirectly) managed	Controlled by concentration limits on cadmium, copper, lead, mercury, nickel and zinc in receiving soil
Nutrients	Application locations (proximity to water courses), timing and rate are controlled by General Binding Rules. Risk of pollution of the water environment must minimised, crop demand for nitrogen not exceeded, and soil phosphorus status maintained at 'acceptable agronomic levels'
Nutrients	Application locations, quantities and timings for biosolids applied to agricultural land within designated nitrate vulnerable zones are restricted – under codes of practice

The principle regulatory instrument controlling the use of biosolids on agricultural land is the Sludge (Use in Agriculture) Regulations (HMSO, 1989). This requires that The sludge shall be used in such a way that account is taken of the nutrient needs of the plants and that the quality of the soil and of the surface and ground water is not impaired. In practice, the regulations limit the rate of accumulation of specified potentially toxic elements (PTEs) in soils to which biosolids are applied. Soils must be tested before biosolids are first applied, and need not then be tested again for another twenty years. However, the biosolids themselves must be tested at six monthly intervals and the ten year average loading rate for specified PTEs (in kg per hectare) calculated.

Soils must be tested for pH, chromium, cadmium, copper, lead, mercury, nickel and zinc – and soil concentrations (on a dry matter basis) are prescribed for cadmium, copper, lead, mercury, nickel and zinc according to pH. Biosolids cannot be applied to soils with pH of less than 5.0.

Spreading activities under the sludge regulations do not require prior notification to SEPA, and any odour complaints arising from agricultural spreading are normally dealt with by Environmental Health departments within local authorities (Quinn et al., 2016).

As an organic fertiliser, biosolids also fall within the scope of The Water Environment (Controlled Activities) (Scotland) Regulations 2011 (as amended). Various General Binding Rules apply to the location of spreading, which must not be:

- Within 10 metres of any:
    - river, burn, ditch or loch, as measured from the top of the bank;
    - wetland;
    - transitional water or coastal water as measured from the shoreline; or
    - opening into any surface water drainage system;
- Within 50 metres of any:
    - spring that supplies water for human consumption; or
    - well or borehole that is not capped in such a way as to prevent the ingress of water.

Biosolids may not be applied to land that:

- Has an average soil depth of less than 40cm and overlies gravel or fissured rock, except where the application is for forestry operations;
- Is frozen waterlogged or covered in snow; or is sloping, unless it is ensured that any run-off of fertiliser is intercepted (by means of a sufficient sized buffer or otherwise) to prevent it entering any river, burn, ditch, wetland, loch, transitional water or coastal water towards which the land slopes.

Biosolids must not be applied to land:

- In such amounts that the crop requirement for nitrogen is exceeded;
- In excess of the amount required to maintain the soil phosphorus status at acceptable agronomic levels; or
- During heavy rainfall or where heavy rainfall is forecast within 24 hours.

The General Binding Rules also require that any equipment used to apply biosolids must be maintained in a good state of repair, and that biosolids must be applied on land in such a way and at such times that the risk of pollution of the water environment is minimised.

Requirements on biosolids' use that derive from the Nitrates Directive (EEC, 1991) are presented in the forms of Codes of Practice, to which farmers must (voluntarily) adhere. Further information on these requirements is presented in Section 0.

Under the wider (waste management licensing) regulations, waste recovery activities (including the application of biosolids to agricultural land) must be undertaken without:

- Risk to water, air, soil, plants or animals; or
- Causing nuisance through noise or odours; or
- Adversely affecting the countryside or places of special interest (SEPA, 2011).

2.2 Good Practice

2.2.1 Sludge treatment

Hazards addressed by good practice	How they are addressed
Pathogens	Compliance with the Safe Sludge Matrix – to produce either Conventionally or Enhanced-Treated sludges. These require that either a $2\log_{10}$ or $6\log_{10}$ kill in pathogens be demonstrated, and that (for Enhanced Treated sludges), Salmonella be absent

As noted above, the relevant regulations require that (unless injected or otherwise incorporated into the soil), sludge must be subjected to biological, chemical or heat treatment, long-term storage or any other appropriate process so as significantly to reduce its fermentability and the health hazards resulting from its use. The regulations do not specify appropriate treatments. However, the Code of Practice for the Agricultural Use of Sewage Sludge (DOE, 2006) provides examples of treatment processes that may be deemed to satisfy the regulatory requirements (Table 2-3).

Table 2-3 Sludge treatment options, as listed in the Code of Practice (DoE, 1996)

Process	**Descriptions**
Sludge Pasteurisation	Minimum of 30 minutes at 70°C or minimum of 4 hours at 55°C (or appropriate intermediate conditions), followed in all cases by primary mesophilic anaerobic digestion.
Mesophilic Anaerobic Digestion	Mean retention period of at least 12 days primary digestion in temperature range 35°C +/- 3°C or of at least 20 days primary digestion in temperature range 25°C +/- 3°C followed in each case by a secondary stage which provides a mean retention period of at least 14 days.
Thermophilic Aerobic Digestion	Mean retention period of at least 7 days digestion. All sludge to be subject to a minimum of 55°C for a period of at least 4 hours.
Composting (Windrows or Aerated Piles)	The compost must be maintained at 40°C for at least 5 days and for 4 hours during this period at a minimum of 55°C within the body of the pile followed by a period of maturation adequate to ensure that the compost reaction process is substantially complete.

Process	Descriptions
Lime Stabilisation of liquid Sludge	Addition of lime to raise pH to greater than 12.0 and sufficient to ensure that the pH is not less than 12 for a minimum period of 2 hours. The sludge can then be used directly.
Liquid Storage	Storage of untreated liquid sludge for a minimum period of 3 months.
Dewatering and Storage	Conditioning of untreated sludge with lime or other coagulants followed by dewatering and storage of the cake for a minimum period of 3 months If sludge has been subject to primary mesophilic anaerobic digestion, storage to be for a minimum period of 14 days

The Safe Sludge Matrix (ADAS, 2001) prohibits the use of untreated sludges on agricultural land, and differentiates between how Conventionally and Enhanced Treated sludges can be used for different cropping scenarios. It does not prescribe the nature of the treatment required to deliver either category of sludge, instead prescribing the required outcomes of any applied treatment:

- Conventionally treated sludges must be subjected to a treatment that destroys 99% (or $2\log_{10}$) of pathogens present;
- Enhanced treated sludges must be subjected to a treatment that destroys 99.9999% (or $6\log_{10}$) of pathogens present, and renders the treated sludge free of Salmonella.

In practice, compliance is determined by monitoring treatment impacts on *E. coli*, as a suitable indicator organism or proxy for ‘pathogens’. Neither the Code of Practice nor Safe Sludge Matrix provide alternatives to scenarios in which $6\log_{10}$ pathogen reductions cannot be demonstrated due to low pathogen populations in untreated sludges. Suitable alternatives are instead provided under the Biosolids Assurance Scheme (see Section 0).

2.2.2 Sludge transport

Hazards addressed by good practice	How they are addressed
Odours and spillages	Vehicles used for transporting biosolids must be suitable for the intended task and ‘adequately contained or covered to avoid odour nuisance’. Any spillages must be cleared-up immediately to prevent risks to water courses.

The Code of Practice for Agricultural Use of Sewage Sludge (DOE, 2006) states the following:

The movement of sludge by road tankers from sewage works to agricultural land can lead to complaints of noise and smell in built-up areas and cause serious traffic problems in country lanes.

- To minimise the risk of creating a nuisance the type and size of vehicle should be suitable for the planned tasks. All sludge loads should be adequately contained of covered to avoid odour nuisance. Care should be taken to ensure that vehicles used to carry untreated sludge do not cross contaminate subsequent loads of treated sludge. The routes should be carefully chosen to minimise inconvenience to the public.
- Spillage of sludge should be cleared up immediately in a manner that avoids pollution of watercourses.

It should be noted that this Code of Practice has been superseded outside Scotland (GOV.UK, 2017). It should also be noted that the requirements listed above do not apply to biosolids being transferred in an agricultural spreader from temporary field stores to the place of application – nor where treatment of sludges (e.g. using a mobile lime treatment rig) occurs at the place where the biosolids are to be used.

2.2.3 Sludge storage

Hazards addressed by good practice	How they are addressed
'Public nuisance'	There is no requirement in the COP to manage odours during storage – whether those stores are permanent or temporary

The Code of Practice (DOE, 2006) requires that sludge storage units must be designed and constructed so that as far as practicable sludge cannot escape from them and members of the public cannot have access to the sludge stored within them. As noted above, this code has been updated and no longer includes Scotland.

Controls on temporary field stores have been established by the Water UK Biosolids Network, although are not listed in public documents. They require that, to minimise the risk of temporary diffuse pollution during the intended period of storage, biosolids cake dispatched for temporary field storage must:

- be solid enough to be stored in a free-standing heap; and
- not be likely to give rise to free drainage from within the stacked material

2.2.4 Sludge use

Hazards addressed by good practice	How they are addressed
Potentially Toxic Elements	Code of Practice limits accumulation of molybdenum, selenium, arsenic, and fluoride in soils to which biosolids are applied
Odours	PEPFAA requires that all odours from agricultural activities be considered and minimised, so that statutory nuisance is avoided
Nutrients	PEPFAA, NVZ guidance and SRUC technical notes all limit rates at which biosolids can be applied to agricultural land. The condition and location of the land must also be considered before application to minimise risks from run-off
Pathogens	The Safe Sludge Matrix prescribes harvest and grazing intervals for Conventionally and Enhanced treated biosolids in different agricultural land uses

Several codes of practice apply to the application of biosolids on agricultural land, including:

1. The PEPFAA Code (Prevention of Environmental Pollution from Agricultural Activity) (Scottish Executive, 2005);
2. Nitrate Vulnerable Zone guidance (Scottish Government, 2016);
3. The Biosolids Nutrient Management Matrix (ADAS, 2014);
4. The Code of Practice for Agricultural Use of Sewage Sludge (DOE, 2006); and
5. The Safe Sludge Matrix (ADAS, 2001).

Many of the relevant requirements of the first three codes are focussed on minimisation of water pollution risks. Thus, application of biosolids to steeply-sloping land, frozen, wet or waterlogged soils must be avoided – as must the application within close proximity of springs, wells, boreholes and other water sources. Application rates are limited according to total nitrogen concentration, while (in NVZs) applications are prohibited during winter closed periods where readily available nitrogen exceeds 30% of total nitrogen. The Nutrient Management Matrix seeks to limit phosphorus accumulation in biosolids-amended soils, to minimise long term risks of phosphorus transfer to sensitive water bodies.

Such approaches directly minimise risks from nutrient transfer – and indirectly minimise risks from other hazards present in biosolids, such as pathogens. The potential for odour during spreading activities) must be considered and managed to prevent odour nuisance. Indeed, the code covers odour potential from all farming activities.

Whilst soil concentrations for several PTEs are controlled under regulation (see Section 2.1.1), the Code of Practice (DOE, 2006) recommends limits for a further four: molybdenum, selenium, arsenic, and fluoride.

When biosolids are applied to the surface of grassland, the addition of lead, cadmium and fluoride in any one year must not exceed 3 times the 10-year average annual rates, and differentiation is made between permissible concentrations of copper, nickel, mercury and chromium and molybdenum when biosolids are applied to grassland as opposed to arable soils. Biosolids cannot be applied to the surface of grassland if their lead concentration is greater than 1,200mg/kg or their fluoride concentration is greater than 1,000mg/kg (on a dry weight basis), irrespective of ten year average loading rates.

Soil sampling depths also vary between land uses – with shallower samples required for permanent grassland (7.5cm) than cultivated land (25cm or soil depth, if shallower).

The Safe Sludge Matrix prevents the application of untreated sewage sludges to agricultural land, and prescribes the circumstances under which either Conventional or Enhanced Treated biosolids can be used (Table 2-4).

Table 2-4 The Safe Sludge Matrix (ADAS, 2001)

Cropping category	Conventionally Treated		Enhanced Treated	
Fruit	✗		✓	10 month harvest interval applies
Salads	✗	30 month harvest interval applies	✓	10 month harvest interval applies
Vegetables	✗	12 month harvest interval applies	✓	10 month harvest interval applies
Horticulture	✗		✓	10 month harvest interval applies
Combinable and animal feed crops	✓		✓	
Grassland and forage – grazed	✗	Sludge must be deep injected or ploughed down; 3 week no graze interval applies*	✓	3 week no graze interval applies
Grassland and forage – harvested	✓	3 week no harvest interval applies	✓	3 week no harvest interval applies
Key:				
✓	All applications must comply with the Sludge (Use in Agriculture) Regulations and DETR Code of Practice for Agriculture Use of Sewage Sludge			

Cropping category	Conventionally Treated	Enhanced Treated
✘	Applications are not allowed, except where stated conditions apply	

*The matrix, as published, is ambiguous on this point – implying that there should be no grazing during the season in which Conventionally Treated sludges are applied. The interpretation presented in the table above is that of the Red Tractor Assurance Beef & Lamb Standards (Red Tractor Assurance, 2017).

2.3 Biosolids Assurance Scheme

Hazards addressed by good practice	How they are addressed
Various	The BAS brings together regulatory and good practice controls, and therefore addresses the ranges of hazards described in previous sections. The BAS also introduces a requirement for Source Material Risk assessments, in which all hazards relevant to the quality of biosolids are brought into scope. In practice, the focus remains on soil PTE concentrations and pathogen kill during sludge treatment.
Pathogens	The BAS disambiguates the situation where raw sludges contain concentrations of fewer than $6\log_{10}$ *E. coli*, which means that $6\log_{10}$ pathogen kill cannot be demonstrated by any specific process. In such circumstances, Maximum Allowable Concentrations (MAC) apply. MAC also apply to Conventionally Treated sludges, although in such cases $2\log_{10}$ kill must also always be demonstrated.

Previous sections have highlighted various regulatory and good practice controls that apply to the production, transport, storage and use of biosolids. These controls have developed over a number of years to meet the changing needs of the biosolids' market, and their diversity can be confusing. The Biosolids Assurance Scheme seeks to provide clarity by bringing regulatory and good practice controls together into a single, auditable, scheme. This unambiguously makes the many (hitherto) voluntary controls compulsory – and Scottish Water have committed to ensuring that all of their sludge treatment centres and downstream sludge management activities comply with the scheme.

Two specific areas are drawn-out in the BAS Standard that are not covered by the various regulatory or good practice requirements:

1. The application of HACCP approaches to pathogen control; and
2. The use of source material risk assessments.

These are considered below.

HACCP approaches to pathogen control

As set out in Section 2.2.1, the Safe Sludge Matrix discriminates between sludges that have been subjected to Conventional or Enhanced treatment. However, no absolute limits are specified for pathogens in the biosolids' product. Furthermore, sludges can be treated in a variety of ways, some of which can deliver similar outcomes in terms of pathogen kill (Section 2.2.1). BAS therefore sets out a process by which samples of untreated and treated sludges are tested for *E. coli* to demonstrate both: $\log_{10}$ kill and compliance with maximum *E. coli* populations in the treated material:

- For Conventional Treatment, a $2\log_{10}$ kill of *E. coli* must be demonstrated. The treated sludge must also meet a maximum allowable concentration (MAC) of 100,000 *E. coli* per gram of dry solids;
- For Enhanced Treatment, a $6\log_{10}$ kill of *E. coli* must be demonstrated, or the treated sludge must meet a maximum allowable concentration (MAC) of 1,000 *E. coli* per gram of dry solids (and no Salmonella).

It should be noted that final product storage and the potential for *E. coli* or Salmonella populations to change during storage are not covered by the HACCP approach under BAS. Whilst process efficacy must be shown by testing samples taken before and after processing, there is no explicit requirement to test samples taken from storage.

Source Material Risk Assessment

Three different categories of source material are listed, with the extent of required risk assessment increasing as the materials diverge from straightforward urban waste waters:

1. Category A – Domestic wastewater and industrial wastewater
2. Category B – Septic tank material and water treatment sludge
3. Category C – Feedstock material (such as green waste used for co-composting with sludges)

Where Category A or Category B materials are processed, then one risk identification and risk control form must be completed for the entire organisation for each category. These forms must then be reviewed at least every thirty-six months and amended where necessary.

If Category C materials are processed, then a pre–acceptance assessment must be completed for each separate feedstock stream supplied. This assessment must be reviewed at least every thirty six months and amended where necessary. A risk identification and risk control form must be completed for each sludge treatment site that receives one or more feedstock material(s), and these forms must be reviewed and updated if there is a substantial change to the feedstock material. Where no substantial change occurs, the risk identification and risk control forms must be reviewed at least every twelve months and amended where necessary.

Copies of the various assessment, risk identification and risk control forms are provided in the BAS standard[2].

[2] https://assuredbiosolids.co.uk/wp-content/uploads/2018/04/BAS-STANDARD-Issue-4-Online-version.pdf

3 Treatment impacts on hazards of interest

3.1 Overview

Modelling has identified eleven hazards of interest in biosolids:

1. Atenolol
2. Benzothiazole
3. Cyclomethicone 5
4. Cyclomethicone 6
5. Triclocarban
6. Nonylphenol
7. NP2EO
8. PBDE99
9. PBDE209
10. PCB118
11. PCB138

As discussed in Section 1.2.4, several techniques are applied to the treatment of sewage sludges in Scotland, principally:

1. Drying and pelletising / granulation
2. Thermal Hydrolysis and Anaerobic Digestion
3. Liming
4. Anaerobic Digestion

When applied adequately, the first three of these techniques are capable of producing biosolids that meet the pathogen reduction requirements of ‘Enhanced Treated’ biosolids (as defined by the Safe Sludge Matrix), whilst anaerobic digestion is capable of producing ‘Conventionally Treated’ biosolids. However, neither the Safe Sludge Matrix nor regulatory controls apply to organic compound contaminants, such as those listed above. In this section, we report the findings of a Rapid Evidence Assessment (REA) that examined whether the common sludge processing techniques are known to impact on these contaminants. Any reductive impact could reduce exposures below those modelled in Section 3 of the Human Health Risk Assessment Report, although further research would be necessary to understand whether any such reductions were significant – or sufficient to deem these hazards of no further interest.

3.1.1 Atenolol

This compound is partially broken down by biological activity during anaerobic digestion. No evidence could be identified to determine its fate during drying, thermal hydrolysis or liming.

Margot et al. (2015) collated data from multiple sources to illustrate the impact of various wastewater treatment techniques on hazards of interest. This review considered partitioning of hazards between aqueous and sludge phases, as well as genuine attenuation. Atenolol was considered to be broken down by biological activity (rather than sorption to the sludge or solid phase), although this activity was only sufficient to reducing incoming concentrations by 41%. D'Alessio et al. (2015) and Ke et al. (2014) cite higher removal efficiencies – as shown in Table 3-1.

Table 3-1 Removal efficiency of atenolol during conventional activated sludge treatment

Compound	Removal efficiency (%)	Reference
Atenolol	63	D'Alessio et al., 2015
	61	Ke et al., 2014
	41	Margot et al, 2015

Malmborg & Magnér (2015) examined the fate of a number of chemical compounds (both spiked and unspiked) in sewage sludges, through a variety of sludge treatments. These compounds included atenolol, while sludge treatments included thermal hydrolysis and anaerobic digestion. The former treatment had no significant impact on atenolol concentrations, whilst they were significantly reduced in the latter. This suggests that a combination of initial (aerobic) wastewater treatment, followed by anaerobic digestion of sludges would maximise opportunities for removal of atenolol. Further studies would be required to determine the presence and fate during anaerobic digestion of atenolol in Scottish sewage sludges.

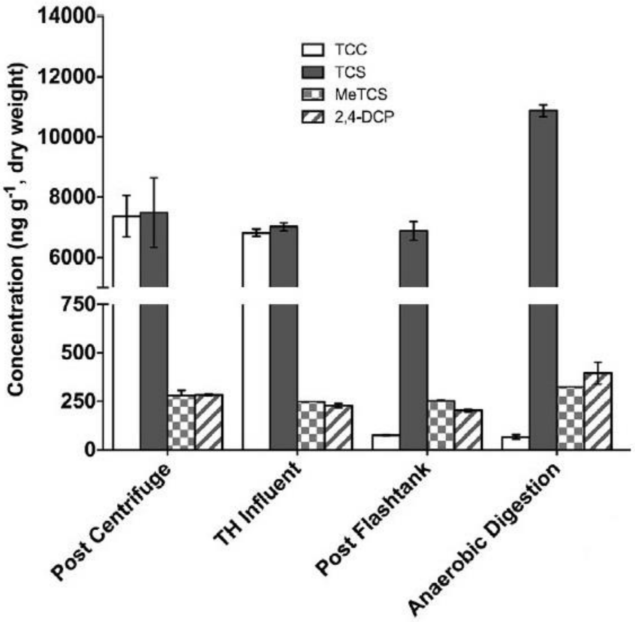
3.1.2 Triclocarban

This compound is partially broken down by thermal hydrolysis. Anaerobic digestion has been found to have little impact, while no evidence is available to determine impact during drying. Liming appears to have little or no impact.

Overall removal of triclocarban (TCC) from waste water can be greater than 95% (Gardner *et al*., 2013), although this removal relies largely on partitioning to biosolids. In a synthesis of multiple sources, Margot (2015) suggests 10% biodegradation during wastewater treatment, with 90% sorption to sludges. Ogunyoku & Young, 2014 indicate that TCC is partly degraded by biological action under aerobic conditions, whole Blair et al. (2015) state a removal efficiency of 11% during conventional activated sludge treatment.

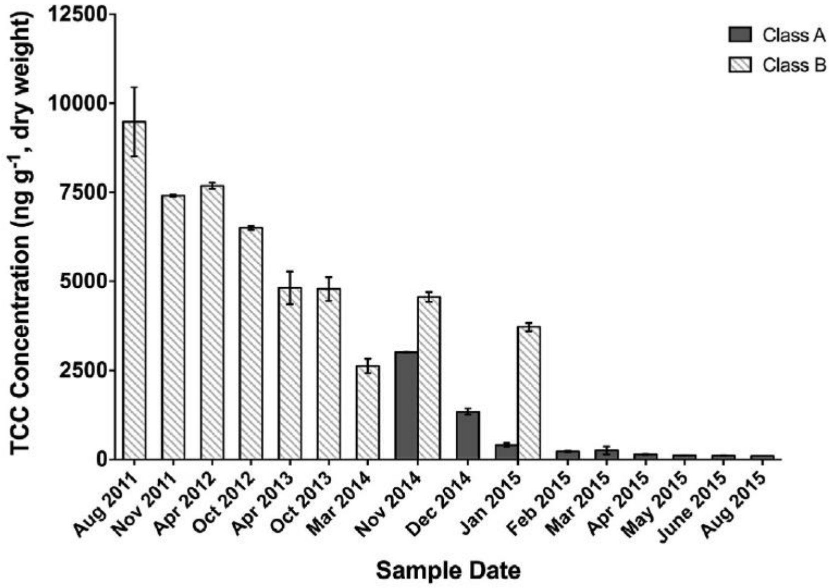
Armstrong et al. (2017) examined the influence of sludge treatment via THP-AD (thermal hydrolysis with anaerobic digestion) on concentrations of triclosan (TCS) and triclocarban (TCC), together with several of their transformation products. The study focussed on sludge treatment centre in the USA that had recently changed its sludge treatment from liming to THP-AD. They found that levels of TCC significantly decreased during thermal hydrolysis. Average concentrations of TCC prior to THP ranged from 6816 to 7368 ngg^{-1} dry weight (dw) while concentrations measured after THP treatment ranged from 67.5 to 89.9 ngg^{-1} dw. The degradation pathways were not determined. In contrast, concentrations of TCS, methyl triclosan, and 2,4-dichlorophenol increased during anaerobic digestion (Figure 3-1).

Figure 3-1 Concentrations of TCC, TCS, MeTCS, and 2,4-DCP at separate stages of the THP-AD process (error bars represent the standard error of the mean). Adapted from Armstrong et al. (2017).



Overall, concentrations of TCC in THP-AD biosolids (Class A) was significantly lower than that of limed biosolids (Class B) ($P < 0.01$). The authors noted that, during the THP-AD start-up period, TCC concentrations in the resulting biosolids continuously decreased until the process had stabilized and been fully commissioned (February 2015), after which concentrations remained relatively steady with a range of 102-294 ngg^{-1} dw (Figure 3-2).

Figure 3-2 Concentrations of TCC in Class A and Class B Biosolids (error bars represent the standard error of the mean). From Armstrong et al. (2017).



Heidler et al. (2006) undertook a sampling campaign at a 'typical' U.S. wastewater treatment plant sized to treat 680 million litres of wastewater a day. A mixture of primary and secondary sludges were subjected to anaerobic digestion at between 35 and 37°C for an average period of 19 days. Samples were collected from influent, final effluent (before and after polishing in a sand filter) and de-watered digested sludge (biosolids). Overall, the authors concluded that anaerobic digestion for 19 days did not promote TCC transformation, resulting in its accumulation in biosolids to concentrations of 51 ± 15 mg/kg dry weight. 76 ± 30% of the compound entering the plant underwent no net transformation and instead partitioned into and accumulated in the final biosolids.

Ogunyoku and Young (2014) examined TCC concentrations in sludges and (resulting) biosolids following a range of treatments that included sludge liming – but were unable to reach any clear conclusions over the impact of this practice on the compound of interest.

3.1.3 Benzothiazole

Published literature suggests that partitioning of this compound to sludges is not an important component of its removal from wastewater, with significant proportions instead removed by biological action during activated sludge treatment. No evidence was identified for the fate of this compound in sewage sludges subjected to the different treatments of interest.

While benzothiazoles (BTHs) are used in a variety of drugs, it is unlikely that these are the primary source in wastewater. BTHs and their derivatives are high-production-volume industrial chemicals – their main use being the vulcanisation of rubber – although they are also used as corrosion inhibitors in antifreeze and cooling liquids, in wood preservation and in industrial processes (Margot, 2015). Given the possible sources, it is thought that BTHs in wastewater mainly originate from urban runoff (tyre abrasion on roads) and household sources (e.g. washing clothes). In addition to BTH, the main BTH derivatives that have been measured in wastewater and sludge are benzothiazole-2-sulfonic acid (BTSA), 2-OHBTH, 2-methylthiobenzothiazole (2-MeBTH) and 2-amino-benzothiazole (2-ABTH).

Removal rates (concentration in influent compared with concentration in effluent) for BTHs have been reported as 50-90% for BTH, 40-66% for 2-OHBTH and 50-80% for 2-MeSBTH (Asimakopoulos *et al*., 2013; Stasinakis *et al*., 2013; Karthikraj & Kannan, 2017).

Asimakopoulos *et al*. (2013) reported that removal from wastewater due to sorption onto biosolids and accumulation in sludge was insignificant for BTH, 2-OHBTH, 2-MeBTH and 2-ABTH. Mass balance analysis suggested that a major portion of BTHs was instead lost or bio-transformed during activated sludge treatment processes.

The predicted boiling point of benzothiazole is 227.0±9.0°C (www.chemspider.com), which could render it susceptible to loss during sludge drying (Section 1.2.2), although no evidence was found to support this suggestion. Further studies would be required to determine the presence and fate during drying, liming, thermal hydrolysis or anaerobic digestion of benzothiazole in Scottish sewage sludges.

3.1.4 PBDE 99 & 209

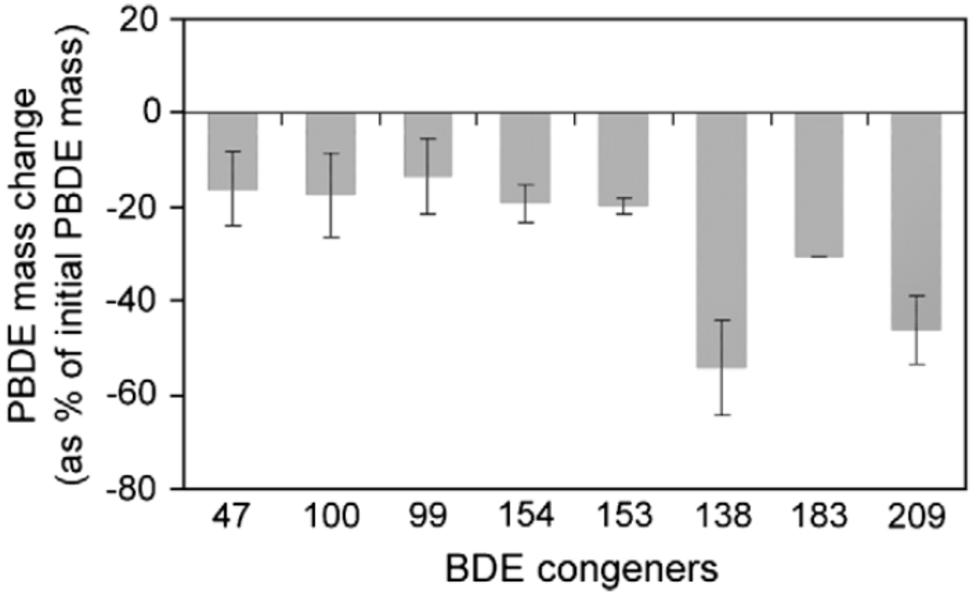
These compounds are partially broken down by anaerobic digestion, with impacts on BDE 209 greater than for BDE 99. No evidence is available to determine impact during thermal hydrolysis or liming. Thermal treatment has been demonstrated to have no impact on BDE 209.

Commercial penta-BDE and commercial octa-BDE were added to Annex A of the Stockholm Convention in May 2009 , while commercial deca-BDE was added in May 2017. A recent review of PBDE concentrations noted a downward trend in sludge concentrations which is likely to be a reflection of the on-going efforts to phase-out PBDEs (Kim *et al*., 2017).

PBDEs enter wastewater treatment plants from contaminated indoor dust, leachate from landfilled PBDE-containing products, and discharge from industrial sites processing PBDE-containing material. Mass balance calculations suggest that 96% of PBDEs are sorbed to sewage sludge (North, 2004).

Shin et al. (2010) investigated the fate of common PBDE congeners (BDE 47, 99, 100, 138, 153, 154, 183 and 209) in sewage sludges under anaerobic conditions (at 37°C). In batch cultures over a period of 238 days, the concentrations of BDE 47, 99, 100 and 209 decreased significantly (by 22–40% from their initial concentration), while concentrations of the other congeners (BDE 138, 153, 154 and 183) remained stable. However, in a parallel study conducted in a pilot-scale anaerobic digester, loss of all eight congeners was observed. The pilot digesters each had a working volume of 535 litres, and their contents were subjected to continuous mixing. The impacts for two different hydraulic retention times were explored: 15 and 30 days (referred to as PSR1 and PSR2, respectively). Data from PSR2 were not presented by the authors, since the digesters did not reach a steady operating state during the experiments. Data from PSR1 are presented in Figure 3-3.

Figure 3-3 Mass changes of eight BDE congeners in sewage sludges in a pilot-scale anaerobic digester with an HRT of 15 days. Mass change was determined as a decrease of PBDE mass in waste sludge as compared to that in feed sludge. Mean ± standard deviation (n = 3). From Shin et al. (2010)



These data show that concentrations of highly-brominated congeners (such as BDE 138, 183, and 209) were significantly lower in the digested sludge when compared with the feed, with reductions ranging from 30.7 to 64.4% by mass. Reductions in the less brominated congeners (BDS 47, 99 and 100) were rather less, at 21.4 and 24.0%.

Mailler et al. (2014) examined the fate of a range of micropollutants at three different wastewater treatment works in Paris, all with different treatment processes. These included thermal drying (at 260°C) and anaerobic digestion. Thermally-dried samples were collected on six different occasions over a period of three months, whilst digested samples were collected on each day over a period of three days. There is a large spread in the resulting data – ascribed to low concentrations and analytical variance, but overall the authors concluded that thermal drying had little to no impact on PBDE 209, and variable impact on nonylphenol and related compounds (Figure 3-4) (see Section 3.1.7 for further discussion of this impact). BDE 209 was significantly removed (>50%) by anaerobic digestion (Figure 3-5).

Figure 3-4 Fate of micropollutants during dewatering processes (from Mailler et al., 2014).

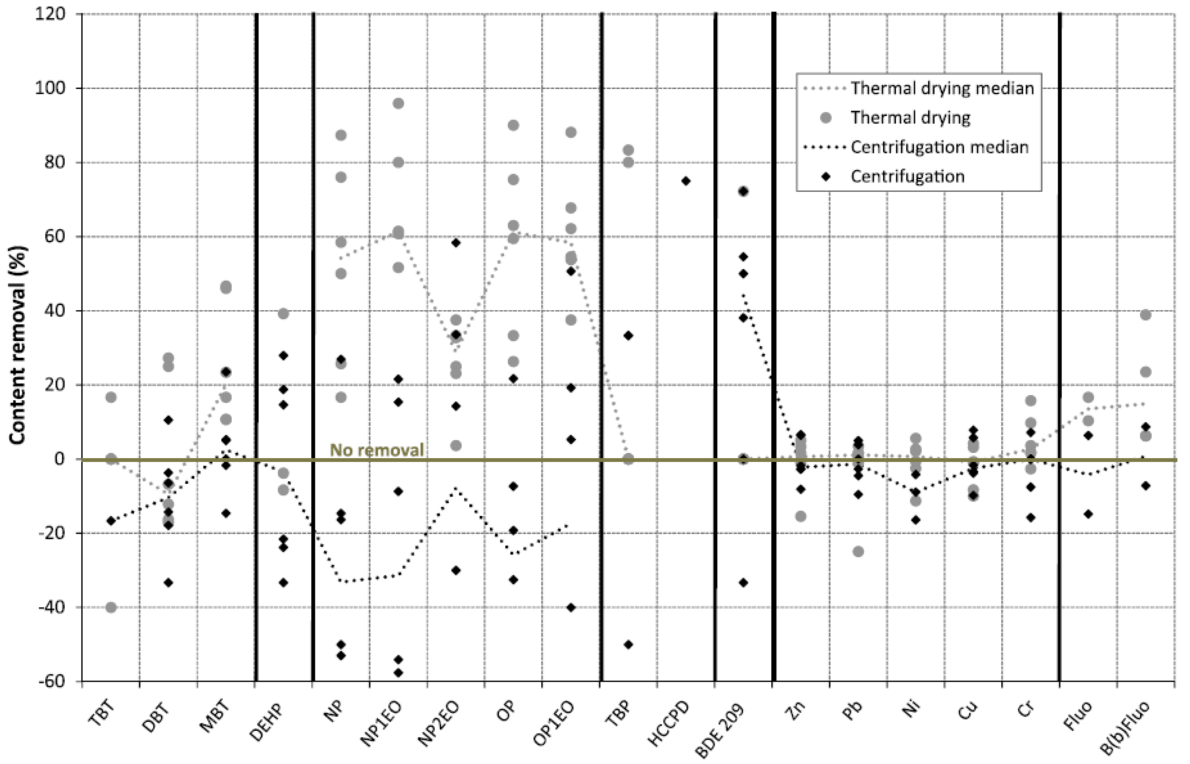
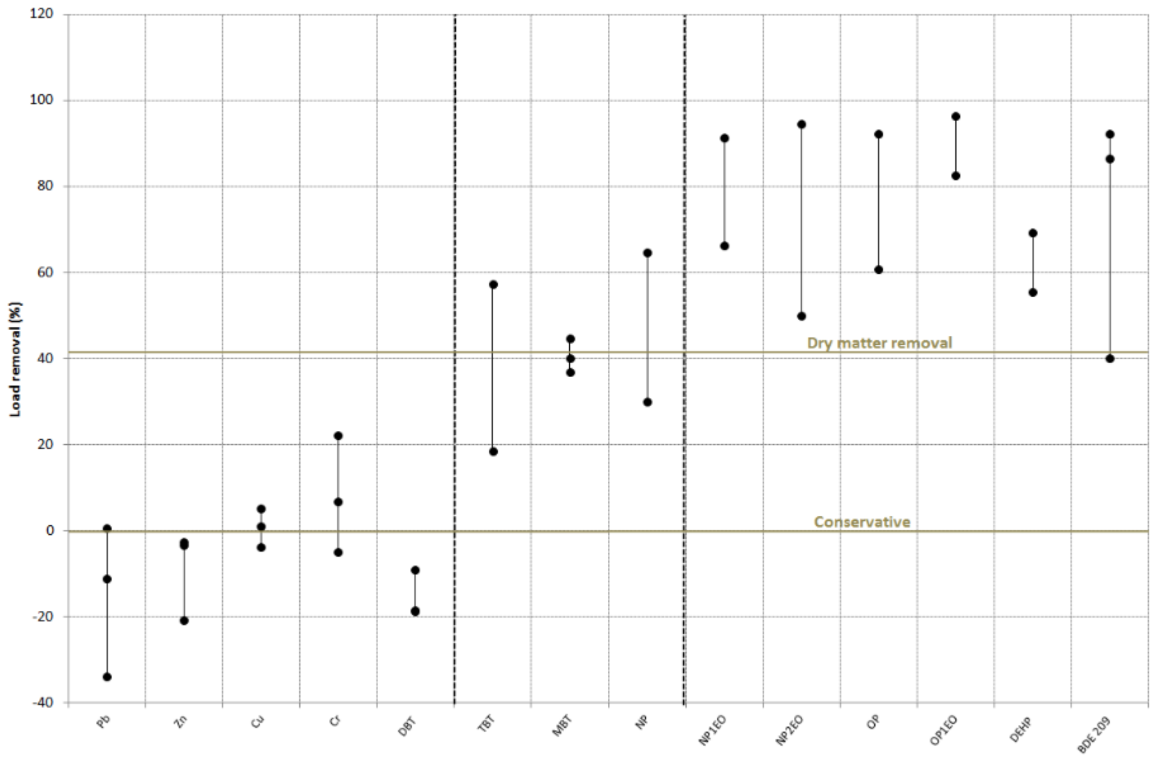


Figure 3-5 Fate of micropollutants during mesophilic anaerobic digestion (from Mailler et al., 2014).



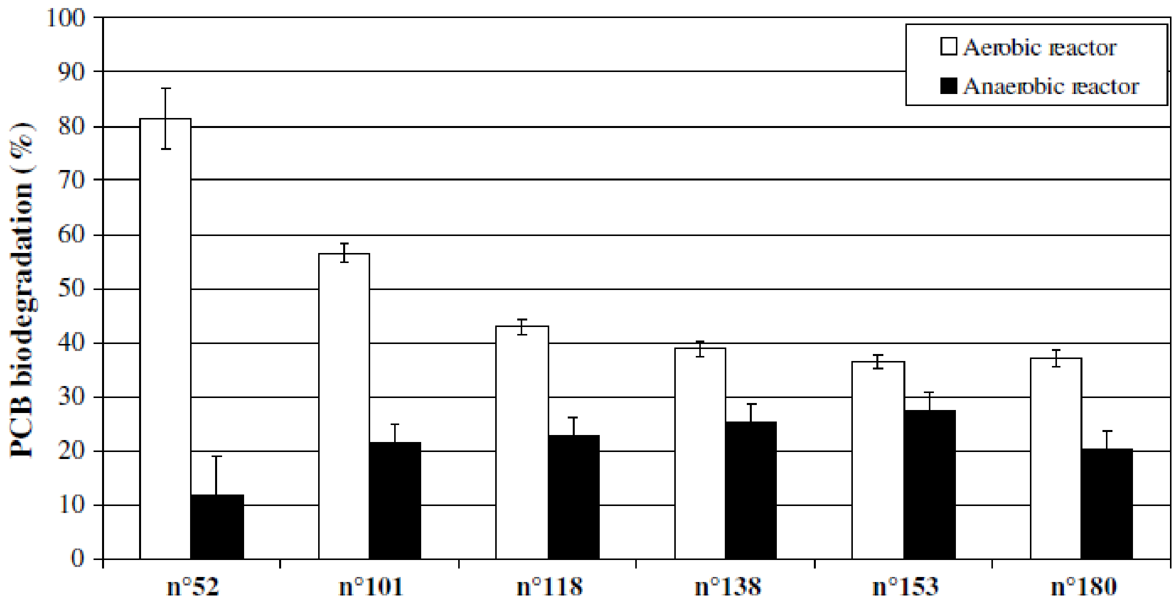
Further studies would be required to determine the presence and fate during drying, liming, thermal hydrolysis or anaerobic digestion of BDE 99 and 209 in Scottish sewage sludges.

3.1.5 PCB 118 & 138

These compounds are partially degraded during anaerobic digestion. No evidence was found that considered their fate during drying, thermal hydrolysis or liming.

Patureau & Trably (2006) examined anaerobic (and aerobic) biodegradation of six PCBs in continuous stirred anaerobic digesters fed with naturally contaminated sewage sludge. PCB removals were about 20% irrespective of PCB molecular weight or degree of chlorination (Figure 3-6). This corresponds well with later data from Siebiełska & Sidełko (2015).

Figure 3-6 PCB biodegradation in anaerobic and aerobic biological reactors at steady state. From Patureau & Trably (2006).



Siebielska & Sidełko (2015) examined changes in PCB concentrations in a mixture of sewage sludge and the organic fraction of municipal waste during composting and during anaerobic digestion at laboratory scale. They concluded that anaerobic digestion was much more effective than composting at removing PCBs from a mixture of sewage sludge and the organic fraction of municipal waste (Table 3-2). Anaerobic digestion was undertaken in 50litre reactors at 39°C over 21 days. Composting was undertaken in 60litre reactors over cycles of 182 days. Concentrations of the more highly-chlorinated PCBs were less impacted by composting than the less chlorinated PCBs. The chlorination level of the PCB congener did not affect the decrease observed during anaerobic digestion.

Table 3-2 Decreases in PCB concentrations during composting and AD. From Siebielska & Sidełko (2015).

PCB congener	Average decrease in concentration during composting (%)	Average decrease in concentration during AD (%)	*F*-statistic value
PCB 28	15.7	18.4	5.70
PCB 52	11.8	18.1	9.38
PCB 101	8.4	20.0	7.83
PCB 118	9.6	18.5	8.40
PCB 138	10.5	20.0	7.09
PCB 153	9.0	23.9	31.28
PCB 180	6.9	21.1	14.25

Further studies would be required to determine the presence and fate during drying, liming, thermal hydrolysis or anaerobic digestion of PCB 118 and 138 in Scottish sewage sludges.

3.1.6 Cyclomethicone 5 & 6

Cyclomethicone 5 is readily volatilised during aerobic and anaerobic treatments, while cyclomethicone 6 is thought to remain in sludges. The impacts on these compounds of drying, thermal hydrolysis or liming are unknown.

Cyclomethicone 5 & 6 are volatile silicon compounds (siloxanes), normally referred to as D5 (decamethylcyclopentasiloxane) and D6 (dodecamethylcyclohexasiloxane).

The presence of volatile silicon compounds in biogas is problematic, since the combustion of contaminated biogas can result in crystallisation of silica within engines – causing significant damage and eventual failure. Activated carbon filters are normally used to scrub siloxanes from biogas before combustion. García et al. (2015) reviewed published data in the presence of siloxanes in biogas from anaerobic digestion of sewage sludges and reported that 93.7% of siloxanes in wastewater are D4 or D5. A significant proportion of these compounds was lost through volatilization during aerobic treatment (58.6%), with the remainder retained in sludge – a proportion of which is then volatilised during AD. D6 was stated to remain in the sludge.

This same finding was reported by Appels et al. (2008), who provide an overview of the occurrence and fate of various siloxane compounds during wastewater treatment. They report that the cyclic siloxanes D4 (octamethylcyclotetrasiloxane) and D5 are detected in significant amounts in biogas from anaerobic digestion of sewage sludges, while larger molecules such as D6 do not volatilise during digestion, remaining in the sludge.

Xu et al. (2013) present a contradictory picture, having examined the occurrence and fate of four cyclic and two linear volatile siloxanes in a municipal wastewater treatment plant in Beijing. Through in vitro biodegradation experiments, they concluded that D6 was eliminated mostly by volatilization, while D5 was eliminated by a combination of volatilization and degradation. However, de Arespacochaga et al. (2015) state that biodegradation of siloxanes is thought to play a minor role in their loss during sludge treatment.

With boiling points of 211°C (D5) and 245°C (D6) (de Arespacochaga et al., 2015), it is possible that both compounds would be lost during sludge drying – although no evidence was found to confirm this. Further studies would be required to determine the presence and fate during drying, liming, thermal hydrolysis or anaerobic digestion of cyclomethicone 5 & 6 in Scottish sewage sludges.

3.1.7 Nonylphenol (NP) and NP2EO

Evidence for removal of NP and NP2EO during anaerobic digestion are contradictory, due to potential for transformation of NP2EO to NP. Thermal hydrolysis has no impact on removal of these compounds, although may reduce the potential for biological transformation of NP2EO to NP. No evidence could be found for impacts of liming on these compounds, which may be partly or completely removed by drying.

Published data on the impacts of sludge treatment process on NP are extremely variable. Stasinakis (2012) reviewed publications exploring the fates of emerging contaminants during sludge processing. Data for reductions of NP and related compounds during anaerobic digestion are summarised in Table 3-3.

Table 3-3 Removal of NP, NP1EO and NP2EO during mesophilic anaerobic digestion of different sewage sludges

Compound	% removal during AD	Solids Retention Time (days)	Type of sludge	Reference
NP	0	30	Primary	Paterakis et al., 2012
NP	100	30	Mixed primary and activated	Paterakis et al., 2012
NP1EO	3.76	20	Activated	Hernandez-Raquet et al., 2007
NP2EO	2.63	20	Activated	Hernandez-Raquet et al., 2007

Mailler et al. (2014) examined the fate of a range of micropollutants at three different wastewater treatment works in Paris, all with different treatment processes. These included thermal drying (at 260°C) and anaerobic digestion. Thermally-dried samples were collected on six different occasions over a period of three months, whilst digested samples were collected on each day over a period of three days. Overall, the authors concluded that thermal drying had variable impact on nonylphenol and related compounds (Figure 3-4). NP compounds (nonylphenol monoethoxylate (NP1EO) and nonylphenol diethoxylate (NP2EO)) were significantly removed during AD (>50%) while NP was moderately removed (40%) by this process.

This is contrast to McNamara et al. (2012), who compared the impacts of thermal hydrolysis and mesophilic anaerobic digestion on NPEs (a collective term for nonylphenol monoethoxylate (NP1EO), nonylphenol diethoxylate (NP2EO) and nonylphenol (NP)), as compared with conventional MAD and aerobic digestion. Three thermal hydrolysis-mesophilic anaerobic digestion (TH-MAD) reactors were operated:

1. Reactor one (TH150-MAD) received sludge that underwent thermal hydrolysis at 150°C followed by MAD with an SRT of 15 days;
2. Reactor two (TH170-MAD) received sludge that underwent thermal hydrolysis at 170°C followed by MAD with an SRT of 15 days;
3. Reactor three (TH150-MAD20) received sludge that underwent thermal hydrolysis at 150°C followed by MAD with an SRT of 20 days.

A conventional mesophilic anaerobic digester (MAD) was fed untreated sludge and served as a control.

Following THP-AD, an aerobic/anoxic reactor was operated under two different conditions:

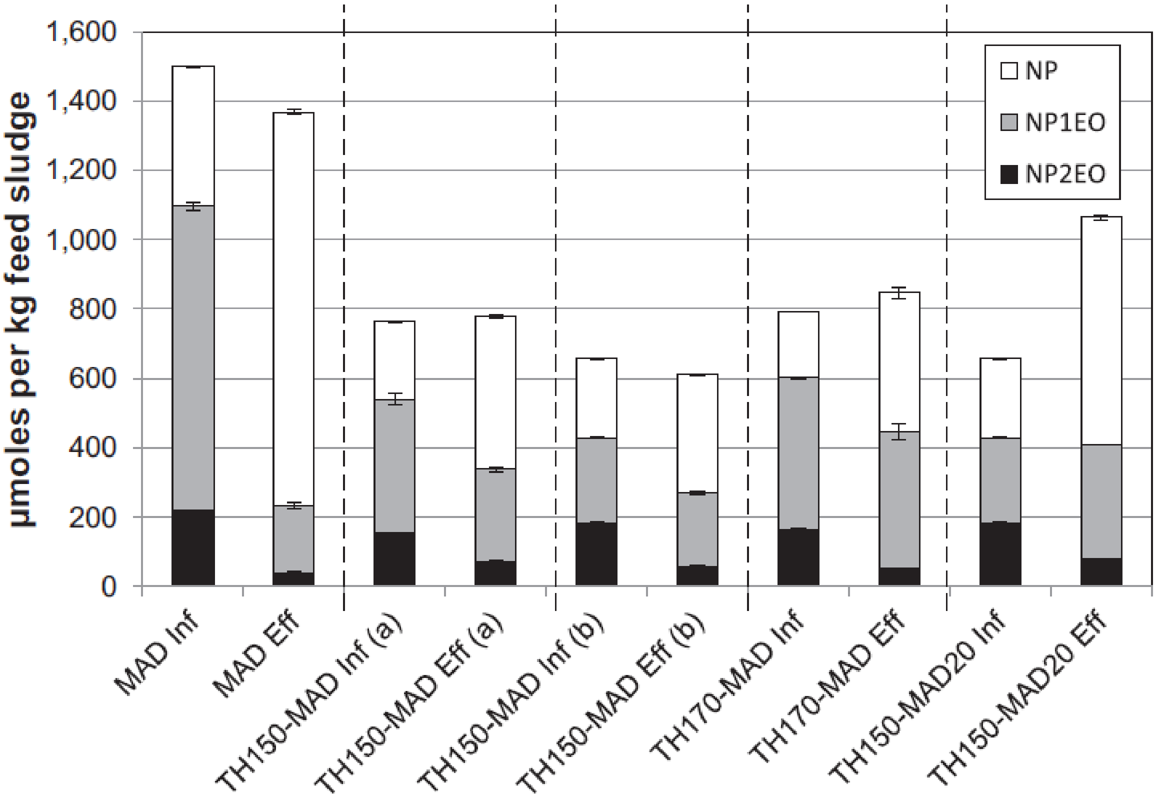
1. Aerobic and anoxic phases were alternated every 20 min. The influent and effluent to this reactor are called TH-M-AER 20/20 Inf and TH-M-AER 20/20 Eff, respectively.
2. Aerobic and anoxic phases were alternated every 12 min. The influent and effluent to this reactor are called TH-M-AER 12/12 Inf and TH-M-AER 12/12 Eff, respectively.

In all anaerobic reactors, with one exception (TH150-MAD20), the total masses of NPE in the influent and effluent were within 10% of each other. The authors interpret this as a demonstration that NPEO was generally transformed to NP, and that substantial loss of NP, NP1EO and NP2EO did not occur during AD, irrespective of prior thermal hydrolysis. Data are presented in Overall, thermal hydrolysis did not reduce NPE loadings in the digested sludges, but did influence the potential for transformation from NPEO to NP – the authors speculate that this may be due to thermal hydrolysis rendering NPEO less bioavailable, and therefore less susceptible to biologically-mediated degradation. However, an aerobic step after digestion did reduce NPE loadings in digested sludges – whether they had first been treated by TH or not.

Figure 3-7.

Overall, thermal hydrolysis did not reduce NPE loadings in the digested sludges, but did influence the potential for transformation from NPEO to NP – the authors speculate that this may be due to thermal hydrolysis rendering NPEO less bioavailable, and therefore less susceptible to biologically-mediated degradation. However, an aerobic step after digestion did reduce NPE loadings in digested sludges – whether they had first been treated by TH or not.

Figure 3-7 Impact of thermal hydrolysis pre-treatment to anaerobic digestion on total NPE in biosolids. Each bar represents the total NPE in each sample, with the individual concentrations of NP2EO, NP1EO, and NP represented as labelled. Error bars refer to standard error of the mean (between triplicate analyses), with the exception of the MAD Eff sample where the error bars represent standard error of the mean on duplicate extractions. From McNamara et al. (2012).



Transformations were also explored by Paterakis et al. (2012). Laboratory scale anaerobic digesters (1.5 litre working volume) were operated in duplicate, with an hydraulic retention time (HRT) of 30 days d at 35ºC. Concentrations of NPEs (including NPECs (nonylphenol ethoxycarboxylates)) were measured at the beginning and end of six retention times for different types of sludge (primary and mixed sludge, the latter comprising primary and waste activated sludge at a ratio of 60% (v/v) primary and 40% (v/v) WAS). Overall, greater removal of ΣNPEOs was observed for the mixed sludge >50% in comparison to primary sludge. However, results were inconsistent, as illustrated in Figure 3-8 and Figure 3-9.

Figure 3-8 Mass flux (mg d^{-1}) for alkylphenol ethoxylates at the start and at the end of the anaerobic mesophilic digestion trial for primary sludge. From Paterakis et al. (2012).

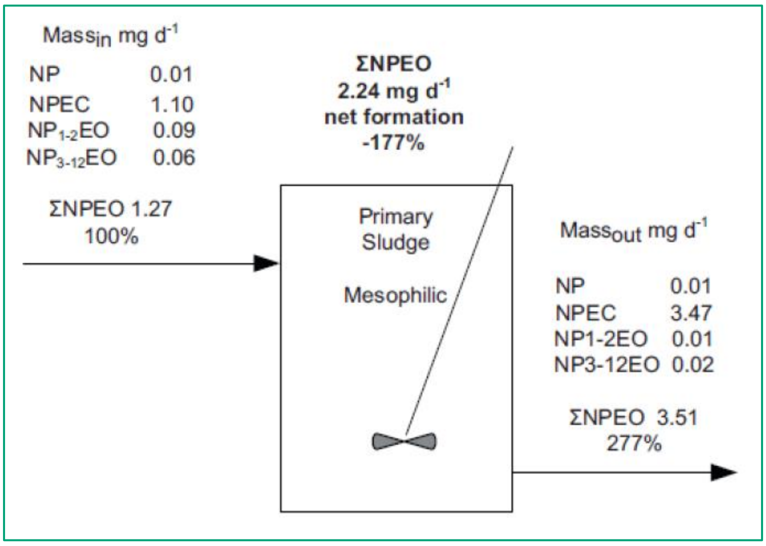
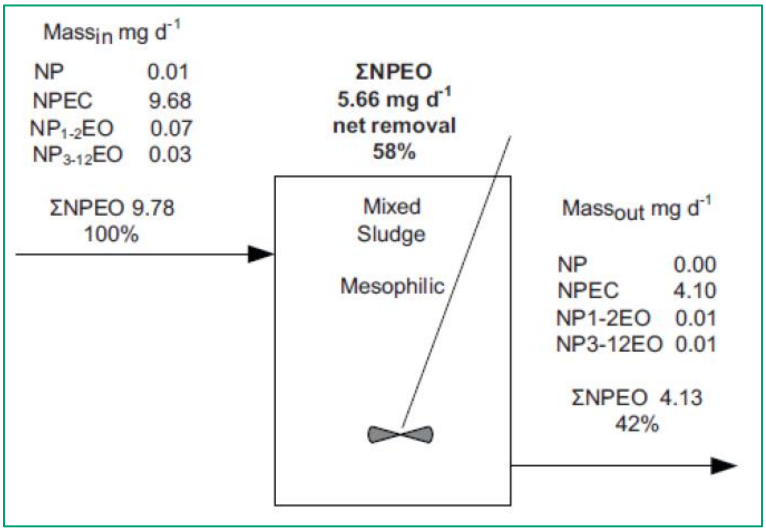


Figure 3-9 Mass flux (mg d^{-1}) for alkylphenol ethoxylates at the start and at the end of the anaerobic mesophilic digestion trial for mixed sludge. From Paterakis et al. (2012).



Further studies would be required to determine the presence and fate during drying, liming, thermal hydrolysis or anaerobic digestion of NP and NP2EO in Scottish sewage sludges.

4 Conclusions

There are 32 Scottish Water and 21 public-private partnership (PPP) sewage sludge treatment sites in Scotland. The majority of sludge destined for agricultural use are produced by the PPP sites (~110,000 tonnes dry solids per year).

Regulatory controls for treatment are split between waste water (which must be sufficiently treated to reach standards that allow it to be discharged into surface waters without undue harm), and sewage sludge treatment (which must be sufficiently treated to reach standards that allow them to be used in thermal energy recovery (incineration) or land-based markets – principally agriculture). There is a conflict whereby (for example) approaches that encourage hazards to partition to sludges (thus improving the quality of the treated waste water) can impact negatively on the quality and usability of the sludges.

There are several best practices guidance for the production, transportation, handling, storage and application of sewage sludge. If adopted augment the regulatory controls, especially with regard to the control of odours and other nuisances.

Most sludges supplied for agricultural purposes have undergone advanced anaerobic digestion, have been thermally dried, or lime pasteurised. These processes are undertaken in order to meet the requirements of the Safe Sludge Matrix (ADAS, 2001). While the focus of these treatments is on pathogen reduction (advanced treatment looks to achieve a 6 log reduction in E. coli and zero Salmonella), these treatment processes can also affect concentrations of other potential hazardous agents including those highlighted by the quantitative risk assessment.

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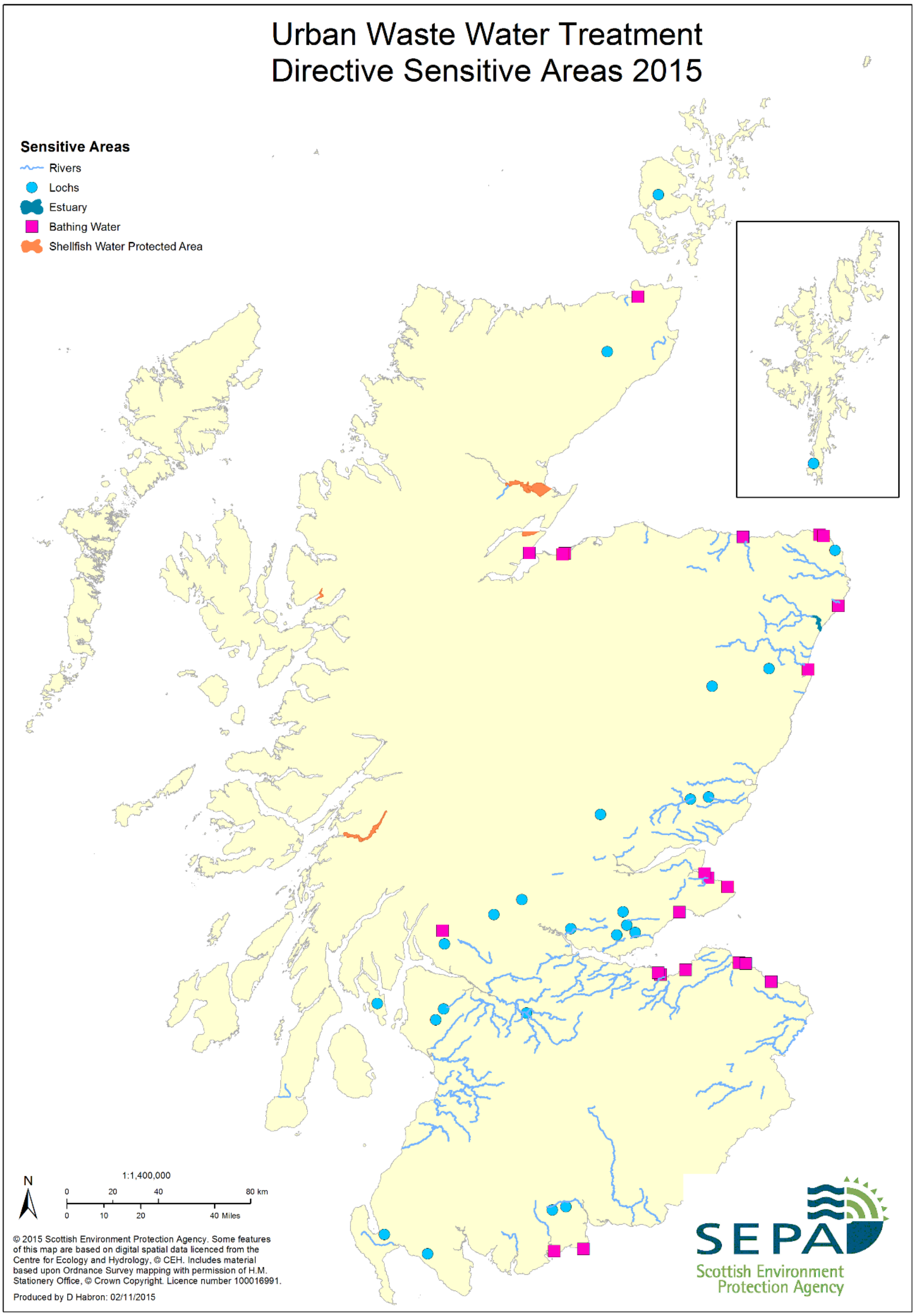
Appendix 1



http://www.gov.scot/Topics/Environment/Water/15561/UWWTDSensitiveAreas/UWWTDSensitiveAreasMap

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