CREW CENTRE OF EXPERTISE FOR WATERS

Applying drinking water treatment residuals to land: opportunities and implications

Applying drinking water treatment residuals to land: opportunities and implications

Authors:
Daniel Gilmour, Ehsan Jorat, Andrew Minto and Irene Tierney.
Abertay University, Bell Street, Dundee, DD1 1HG.

Matt Aitkenhead, Malcolm Coull, Rupert Hough.
James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH.

CRE W CENTRE OF EXPERTISE FOR WATERS

Published by CREW – Scotland's Centre of Expertise for Waters. CREW connects research and policy, delivering objective and robust research and expert opinion to support the development and implementation of water policy in Scotland. CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes supported by MASTS. The Centre is funded by the Scottish Government.

Authors: Daniel Gilmour, Ehsan Jorat, Andrew Minto and Irene Tierney.
Abertay University, Bell Street, Dundee, DD1 1HG.

Matt Aitkenhead, Malcolm Coull, Rupert Hough.
James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH.

CREW Project Management: Irene Fortune, Jenny Rowbottom and Rachel Helliwell (2022).

Please reference this report as follows: Daniel Gilmour, Ehsan Jorat, Andrew Minto, Irene Tierney Malcolm Coull, Matt Aitkenhead, Rupert Hough (2022), **Applying drinking water treatment sludges to land: opportunities and implications**. CRW2019_01. Available online at: crew.ac.uk/publications

ISBN number: 978-0-902701-05-2

Dissemination status: Unrestricted

Acknowledgements: We acknowledge the valuable input and contributions from the steering group for the report, Alan Cundill (SEPA), Claudia Erber (SEPA), Gillian MacAulay (Scottish Water), Christine Murray (Scottish Water), Lorna Macarthur (Scottish Water), Robin Waddell (Forestry and Land Scotland).

We thank Alex Sinclair (SAC) for reviewing and commenting on the report.

Cover photographs courtesy of: Robin Waddell and Daniel Gilmour.

Contents

Executive Summary

Background

In 2018/19, Scottish Water's treatment processes generated c.29,000 tDS[2] (tonnes dry solids) of Water Treatment Residuals (WTR). WTR (also termed drinking water treatment sludges or bioresource) are produced due to the addition of chemical coagulants to water and are a mixture of water, organic and inorganic matter that coagulates during the treatment process. They may contain metals such as iron, aluminium and manganese that have been oxidised as part of the process or are constituents of the coagulation chemicals used. The metals within WTR are of interest with regards to applying these sludges to agricultural land. WTR can also contain beneficial organic matter and nutrients (primarily nitrogen). The nature of the benefit delivered is dependent largely on the quality of the raw water and these beneficial components are generally in much smaller quantities than are found in sewage sludges, produced from wastewater. However, WTR can still be used to enhance the physical properties of soils, which may improve drainage.

Forestry and Land Scotland (FLS) have been working with landowners and other partners since 2016, in a now well-developed programme to restore former opencast mining sites to a state suitable for woodland creation. The process followed by FLS contributes to Scotland's Climate Change Plan (2020), Zero Waste Plan (2010), Circular Economy Bill (2019), helps to meet targets to reduce the area of Scotland's Vacant and Derelict Land and provides other public benefits, including employment through timber production, carbon capture, greater accessibility, and increased biodiversity, all whilst ensuring the recycling of valuable materials. WTR, in combination with untreated wastewater sewage sludge cake, have been recycled as part of land restoration projects for several years to provide much needed organic matter and nutrients to extremely poor soils.

The Scottish Water Bioresource Strategy (underpinned by the principle to maximise the value of WTR) has identified the need to transition the outlet for WTR from purely land restoration to agricultural land due to:

- The likely significant increase in tonnage of WTR over the next 25 years.
- Increasing costs of landfill charges.
- The reduced lifespan and higher operating costs of restoration sites.
- Environmental sustainability and reduction in transportation.

This study is designed to support this transition to agricultural land by understanding the implications of applying WTR to land. The study incorporates a literature review of existing academic and grey literature, and a review of other countries regulation. Based on the findings of the literature review, a user-friendly, decision support tool for guiding the application of WTR to land in Scotland has been developed.

Research questions

The key research questions addressed in this project are:

- What are the benefits and disbenefits of applying drinking water treatment sludges to land? How does this fit in the context of the circular economy in Scotland?
- What is best practice in terms of application? What information (e.g., which analyses of sludge and soil) is required to allow a proper assessment of the suitability for application to land? Which measures could help to mitigate the disbenefits?

Key findings

The application of WTR to land has predominately resulted in the improvement in soil physical properties such as water retention, porosity, hydraulic conductivity and P storage capacity without negative impacts on groundwater. However, no significant change in plant yield was reported after the application of WTR. Application of WTR with a separate application of other types of fertilisers, such as manure or compost, could enhance plant yield and the nutrient status of receiving soils.

Legislation and policy currently dictate that WTR are wastes. Therefore, in Scotland, the application of WTR on land for agricultural benefit or ecological improvement requires SEPA to grant an exemption under either paragraph 7 or paragraph 9(1)(b) of Schedule 1 of the Waste Management Licensing Regulations (2011). These exemptions control the type, quantity, and storage of such wastes when they are to be spread to land. We recommend that the control of WTR land spreading, under exemptions, is maintained and that spreading follows the principles of General Binding Rule 18, particularly considering the season, prevention of pollution of waters by maintaining appropriate buffer strips (e.g., 10 m for surface watercourses/ditches, 50 m for springs, or boreholes etc).

In terms of the circular economy, the procedure of reusing WTR for alternative applications satisfies the Scottish Government's goals in terms of waste prevention and reducing the amount of material being sent to landfill as set out in the Proposals for Legislation in 2019 (Scottish Government, 2019). In 2019, the Scottish Government set targets of reducing waste arising by 15% against the 2011 baseline by 2025, having no more than 5% of all waste being sent to landfill by 2025 and no biodegradable municipal waste being sent to landfill by 2025.

This study found that sole application of WTR seems to be suitable for land restoration. However, if separate applications of fertilisers such as compost, manure or Wastewater Treatment Residuals (WWTR) are made WTR application could enhance soil and plant properties in agricultural land and forestry.

Application of WTR to lands with pH<5.5 should be avoided, given the potential for the Al in the WTR to become soluble and toxic to plants. Before application, properties of WTR and receiving land (e.g., particle size distribution, pH, nutrition values and organic content) should be analysed to evaluate suitability of using WTR for the specific circumstances of the location. The proximity of Scottish Water's Water Treatment Works (WTW) to receiving land should be considered to avoid excessive transportation costs and carbon emissions.

An important aspect in determining an appropriate application rate is the identification of key constituents (e.g., nutrients and potentially toxic element (PTEs)) and their concentrations within the WTR and the receiving soil. Application of WTR to land, for purposes stated above, must undergo suitable analyses to allow the most appropriate spread rate to be determined to match the nutrient requirements of the crop (Appendix 6). The receiving soil will also undergo similar testing, as detailed within good practice guidance in Prevention of Environmental Pollution from Agricultural Activity (PEPFAA), thus helping to ensure that 'Good Agricultural and Environmental Condition' is maintained. The potential benefits and disbenefits have been identified through the literature review and are summarised in Table E1.

Table E1. Potential benefits and disbenefits of applying WTR to land

Potential benefits of applying WTR to land	Potential disbenefits of applying WTR to land
• Improving hydraulic conductivity. • Increasing P storage capacity. • Increasing porosity. • Supplying nutrient elements such as K, N, S and Mg. • Possibly supplying P, if not readily desorbed. • Improving soil physicochemical properties (i.e., pH, electrical conductivity, water holding capacity, cation exchange capacity, organic matter content and soil aeration). • Controlling runoff pollution and/or phytotoxicity of heavy metals. • Absorbing organic and inorganic pollutants (less understood). • Enhancing nutrient recycling in agricultural soils. • Improved performance of plant root system. • The benefit from WTR application to land can be enhanced if a separate vermicompost or poultry litter application is also made. • Successful application for land restoration.	• Unsuitable for soils with pH < 5.5, due to high Al content and increasing toxicity of Al at lower soil pH. • Decreasing available phosphorous and • Deficiencies in plant tissue due to sorption – by Al and Fe oxides. • May require other types of fertilisers to be spread separately to negate crop yield reduction caused by phosphorus sorption. • Some WTR contain high levels of fine particles, therefore are unsuitable for agricultural land spreading where fine-textured soils are present as this may reduce soil porosity. • Commonly require dewatering prior to transportation which entails additional carbon emissions. Though, if transported without de-watering, this can increase the carbon footprint. • May not contain sufficient/right balance of nutrients to support good crop growth.

Recommendations

This project evaluates the opportunities and implications of applying WTR to land and associated circular economy benefit, based on a synthesis of international literature. From this, the following recommendations are proposed:

Application – WTR can provide useful amounts of major and secondary nutrients, and the project has identified possible ways forward for regularly applying WTR to agricultural and forestry land, and for one-off use on restoration sites. For WTR to be approved for application, benefit to ecology or agriculture must be demonstrated. However, ultimately, the application of WTR is dictated by the properties of the receiving soil and requirements of the vegetation. The WTR application rate should be determined by annual soil tests. In agriculture and forestry, WTR can be applied as a sole treatment (regulated under the waste management controls), and a separate application of non-waste fertilisers (e.g., manure or slurry) may be made. When applying WTR to restoration sites, a separate application of biosolids may be recommended to reduce risks of under-provision or inadvertent immobilisation of key nutrients, particularly phosphorus. WTR and biosolids may also be beneficial for restoration activities compared with using biosolids alone, as WTR typically provides more stable organic matter than biosolids. It is recommended that control of WTR land spreading under exemptions is maintained and that spreading follows the principles of General Binding Rule 18, particularly taking into account the season and prevention of pollution of waters by maintaining appropriate buffer strips. However, consideration should be given to exploring the possibility of getting an End-of-Waste status for WTR in the long term.

Application rate – Annual WTR application rate of 50-150 t ha^{-1} to agriculture land has predominately been regarded as suitable in published literature. In England and Wales, application rates for agriculture are typically in the range of 20 – 60 t ha^{-1}. It appears that routine monitoring of soil properties and crop/tree growth is either not widely carried out at WTR spreading sites and/or data from such monitoring has not been widely reported, leading to limited knowledge of the long-term benefits/ impacts of WTR use on both agricultural and forestry land. Further investigation into WTR application to land is required through test applications to understand changes to physical and chemical soil properties and increased monitoring of long-term effects of WTR spreading. With application to land becoming more prevalent, leading to a fuller understanding of the above, a more accurate range of application rates that are likely to be suitable for Scotland can be determined.

Circular economy – The project has identified benefits in relation to the principles of the Circular Economy through increasing the use of WTR on agricultural land. Benefits to the circular economy in Scotland are achieved by reducing distance travelled from SW Water Treatment Works to local application locations. Additional benefits are through the valorisation of the WTR, where the beneficial nitrogen content of WTR can displace the use of nitrogen-based fertiliser, leading to a reduction of CO_2 emissions, in keeping with principles of circular economy and contributing to climate change mitigation. More information is required to develop a full lifecycle analysis to explore the most beneficial use of WTR within a circular economy. The life cycle analysis process will enable a detailed comparison to be made between different outlets for WTR alongside application to land, with a view to maximising circular economy benefits.

Circumstances when to use and not to use WTR – The project has identified circumstances in which to use and not to use WTR based on composition and receiving soil properties. Where there is a need for major and secondary nutrients, WTR can be used. WTR is useful to increase total nitrogen content in soil and may increase organic matter content. WTR is useful in providing high sorption capacity, especially for phosphorus, and for increasing soil cation exchange capacity. WTR is unsuitable for use with soils with pH <5.5 and in soils high in extractable sulphur (>50 mg kg^{-1} TN685 FAS). In Scotland, leaching of P is less likely than in other parts of the world, as Scottish soils tend to have lower pH and significant P fixation by Al occurs at pH values below 6. According to SRUC Technical Note TN714, 64% of arable and grassland soils in Scotland have a soil pH of 5.5-6.25, with 20.3% above and 16.1% below this range. Therefore, erosion and runoff are more likely mechanisms for P transport to streams and water bodies following WTR spreading in much of Scotland. Lateral flow transport of dissolved P through soil is also a risk if there is heavy rainfall soon after WTR application.

Pre-application analysis – Alongside acknowledged pH and nutrient content parameters, particle size distribution of both the receiving soil and WTR should be analysed to ensure particle size suitability for the chosen application. Some WTR tend to have a high percentage of fine particles thus, if flooding is a concern, it may not be appropriate to apply fine-grained WTR to land as this may reduce hydraulic conductivity of soil. If water retention is an issue, (i.e., the receiving soil is sandy) then application of a fine-grained WTR will result in an increase in water retention capacity which is likely to be beneficial.

Further research

The report has highlighted areas where further research needs to be conducted for better understanding benefits and disbenefits of applying WTR to land. Application of WTR to land should continue, with appropriate monitoring, whilst further desk and field work is undertaken to understand the full benefits and disbenefits of the application of WTR to soil properties in the Scottish context, for example:

- Scottish field trials to investigate WTR impact on plant growth and uptake of nutrients in plants.
- Develop a database of soils that can receive WTR, that is accessible to both SEPA and SW, building on site investigation and sample analysis.
- More monitoring of long-term effects of WTR spreading.
- Develop a full lifecycle analysis to explore the costs/ benefits of land spreading WTR to achieve circular economy goals.
- Analyse WTR impact on Scottish soil physical and chemical properties.
- Assess public perception of WTR use on agricultural food production, land restoration, forestry, and ecological benefits.
- Further develop the Decision Support Tool (DST) to incorporate layers of existing soil data into an online system, to enable integration and improved access that makes use of platform independent Javascript or Rshiny.
- Develop a data visualisation app which will automatically adapt to the device used. This will assist the integration of data and engage with real time agronomic data in the field.

1 Introduction

Scottish Water, Scottish Environment Protection Agency (SEPA) and Forest and Land Scotland (FLS) are investigating the feasibility of future widespread application of water treatment residuals (WTR) to land. Developing an agricultural outlet for WTR is important to Scottish Water due to the reducing availability of land restoration outlets. In this report, 'Land' includes agricultural and forestry land, as well as derelict sites where WTR are used for restoration purposes, including former opencast coal sites.

1.1 Background and scope

WTR are generated as part of the drinking water treatment process. In Europe, several million tonnes of WTR are produced every year, and there are considerable concerns about the costs associated with disposal of these materials (Babatunde & Zhao, 2007). Originally, WTR were disposed of in the same water source where drinking water was taken from, until stricter environmental regulations were introduced in Europe in the 1940s (Babatunde & Zhao, 2007). The management of WTR, as opposed to Waste Water Treatment Residuals (WWTR) from Waste Water Treatment Works (WWTW), (also often referred to as 'sewage sludge' or 'biosolids'), is a challenge as the lower nutritional and calorific value of WTR make biological digestion or incineration impractical (Ulmert & Sarner, 2005), whilst their high metal content limits the reuse of WTR in some applications and the large quantities of bound water make dewatering and transport difficult (Babatunde & Zhao, 2007).

Despite the challenges associated with WTR management, there is recent, growing interest in their reuse, likely due to the increased costs of disposal and the move towards a circular economy model of waste management. In Scotland, Forestry and Land Scotland (FLS) have been working with Scottish Water, landowners and other partners since 2016 in a now well-developed programme to use WTR to restore former opencast mining sites to a state suitable for woodland creation. Scottish Water's (SW) interest in use of WTR on agricultural land has increased because the gradual completion and closure of opencast coal sites and restoration of these means that opportunities to use WTR in land restoration in the future will decline. SW's desire to find alternative routes of reuse fits well within the current policy landscape. Relevant policy goals, statutory commitments, and policy decisions include:

- Scotland's Zero Waste Plan (2010)
- Scotland's Circular Economy strategy and bill proposals (2019)
- Climate Change Plan (2018)
- Scotland's Programme for Government 2020-21
- Net Zero Carbon Emission Targets for Scottish Water 2040
- Water Industry Vision
- Scotland's 2045 net-zero emission target
- Scottish Water Bioresource Strategy
- Waste Management Licensing (Scotland) Regulations 2011 (exemptions – paragraph 9, 7)

1.2 Project objectives

The aim of this project was to identify information on best practice, benefits and disbenefits of applying WTR to land, including in the context of the Circular Economy in Scotland, and present this information in a user-friendly decision support tool.

Objectives

a. To produce a written review of academic literature, grey literature and historic data provided by Scottish Water, to understand the history and the implications of applying WTR to land. This is to include:

i. A summary of policy regulations and guidance in other countries and details of management practices and lessons learnt.

ii. Discussion of the benefits and disbenefits (to agriculture, forestry, soil, soil water, water quality, ecology, human health, all aspects of the circular economy and any other environmental issues) and how to mitigate against them if applying WTR to land.

iii. Current views of frequency of application, parameters, and specific analysis for WTR and soil sampling and analysis regime.

iv. Consideration of if/how the principles of the Circular Economy are reflected in application of WTR to land. To include consideration of the implications of replacing other materials, that would normally be used to achieve the same effect, with WTR, other potential options for the use of the material (other than application to land) and the pros and cons between those.

b. Develop a user-friendly decision support tool for applying WTR to land in Scotland that takes into consideration the end land use.

1.3 Outline of the report

The report is organised as follows:

- A literature review, using data and information sourced from academic and grey literature, a summary of policy regulations, discussion of the benefits and dis-benefits, current views of frequency of application, parameters and specific analysis for WTR and soil sampling and analysis regime.
- Summary of application rates, technical requirements, and management in a Scottish context.
- Summary of the user-friendly decision support tool for applying WTR to land in Scotland. The Decision Support Tool is discussed in section 4 and in Appendix 5 (the DST is available as a Microsoft Excel file on the CREW website (https://www.crew.ac.uk/)).
- Conclusions and key recommendations.

2 Literature Review

2.1 Introduction

The standard processes for drinking (potable) water treatment typically include coagulation/flocculation, sedimentation, filtration, disinfection and pH correction. Coagulation is used to remove sediment from the water before supply to customers. To achieve coagulation, aluminium (Al) salts are added to water which results in the formation of alum sludges (Zhao et al., 2011; Zhao, 2002; Yang et al., 2006; Dassanayake et al., 2015) which are commonly referred to as water treatment residuals (WTR). Using Al salts to achieve coagulation for water treatment is currently the main practice in Scotland (95% Al based), however ferric salts have also been used at a very small scale (5% are ferric based).

After coagulation, WTR can be dried to reduce the by-product's moisture and hence facilitate transportation. This method is also the most widely used treatment technique internationally (Dassanayake et al., 2015).

It is estimated that water treatment results in 1-3% of WTR by volume of the pre-treated water (Blakemore et al., 1998). Internationally, a large portion of WTR disposal is via landfill which results in disposal costs being added to overall water treatment costs (Turner et al., 2019). When WTR is deposited into landfills, the transport distance associated with disposal is of growing concern given recently defined carbon emission targets, internationally, nationally (i.e., Scotland's 2045 net-zero emission target https://www.gov.scot/policies/climate-change/) and at a business level (i.e., Scottish Water's net zero target by 2040 https://www.scottishwater.co.uk/about-us/what-we-do/net-zero-emissions-routemap).

In Scotland, over the last few years, the majority of WTR have been used for land restoration as shown in Table 1. Between April 2017 and March 2018, 92% was used for land restoration, similarly between April 2018 and March 2019, 93% and April 2019 and November 2020, 95% of WTR have been used for land restoration. With increasing numbers of completed restoration projects (e.g., opencast coal mines), soon there will be a significant amount of WTR in Scotland with no clear outlet for reuse. Assessing suitability of WTR for future land application in agriculture and forestry is important to explore future opportunities to reuse this potential resource. This report will focus on alum WTR, as the treatment of water with Al salt is the technique generally used in Scotland. Table 1 summarises WTR production in Scotland between 2017 and 2020.

2.2 Compatibility of WTR for land application

2.2.1 Characteristics and variability of WTR

The characteristics of WTR depends on factors such as initial characteristics of water and method of treatment (Turner et al., 2019). Water acquired from surface or underground water sources contain various types of suspended solids from clay to sand sized particles. During water treatment, the suspended solids are collected which comprise a portion of WTR. Using Al salt for treatment of water is an effective and low-cost technique. Alternatively, using ferric salts has been reported as a flocculant for water treatment (Moran, 2018). However, alum WTR is reported to be less toxic than ferric chloride sludge (Dassanayake et al., 2015). Porous organic polymers have

Table 1. WTR production and disposal/reuse in Scotland (in tonnes)

	April 2017 to March 2018				April 2018 to March 2019				April 2019 to November 2020			
Area	Land Rest	Land fill	Agri.	Total	Land Rest	Land fill	Agri.	Total	Land Rest	Land fill	Agri.	Total
North	0	721	1895	2616	0	714	1291	2005	0	527	694	1221
East	5671	0	0	5671	5037	0	0	5037	4118	0	0	4118
West	12228	0	0	12228	11089	0	0	11089	10145	0	0	10145
South	12199	0	0	12199	11042	0	0	11042	8191	0	0	8191
Total	30098	721	1895	32714	27168	714	1291	29173	22454	527	694	23675

been also reported as an effective coagulant for water purification (Sun et al., 2020).

WTR are primarily composed of $Al(OH)_3$ or $Fe(OH)_3$ (depending on coagulant used), organic matter, clay particles, nutrients, contaminant metals and other impurities removed from treated water (Howells et al., 2018). WTR collected from the treatment plants contain high water content (2-4% solids) and accordingly, dewatering is a common practice before transportation of WTR (Dassanayake et al., 2015). Summary of WTR physical and chemical properties are presented in Table 2.

WTR have high porosity (Yang et al., 2006), resulting in high water holding capacity. In addition, they have reactive surfaces, due to presence of Al or Fe hydroxides, providing a high sorption capacity (Makris et al., 2004; Ippolito, 2011). WTR (air dried and crushed to less than 2.0 mm) typically have a high cation exchange capacity of around 13.6 to 56.5 cmol+ kg^{-1} compared to around 3.5 to 35.6 cmol+ kg^{-1} for typical soils (Dayton and Basta, 2001). It is suggested that WTR can retain from 1,740 to 37,000 mg phosphorus (P) kg^{-1} (it is not clear whether this is on dry or wet weight basis) and for WTR, the sorbed P is not readily desorbed (Ippolito et al., 2011). Zhao et al. (2018) reported average nitrogen content of around 5 g kg^{-1}, with phosphorus, potassium and magnesium, content each of around 2.5 g kg^{-1}. Furthermore, 12.0 ± 18.7 g kg^{-1} of the essential plant nutrient manganese was reported for WTR (Zhao et al., 2018). Table 3 presents typical total major nutrient content of WTR from the UK and Scotland.

Table 2. Summary of WTR physical, chemical, and mechanical properties.

Property	Description
Particle size distribution	Uniform distribution of particle sizes (Mokonyama et al., 2017). Sand content 60.4–69.0%, silt content 17–23% and clay content 14–16.6% (Dassanayake et al., 2015).
Specific gravity	Normally, lower specific gravity than topsoil which is attributed to the higher organic content in WTR (Mokonyama et al., 2017). To produce fully dried WTR pallets, Ren et al. (2020) suggested room-temperature drying for 3-days and then 24 hrs oven drying at temperature of 110 °C. Specific gravity of solids ranges between 1.8–2.2 (Turner et al., 2019).
Compaction	WTR cannot be fully dried *in-situ* as this results in destruction of soil structure and calcification of particles (Mokonyama et al., 2017). Bulk density and dry density values of partially dried, but otherwise untreated, WTR (~ 10–40% w/w dry matter) range between 1.0–1.2 t m^{-3} and 0.12–0.36 t m^{-3}, respectively (Turner et al., 2019).
Shear strength	Values vary depending on solids content but in general increases with increasing solids content (Mokonyama et al., 2017). Effective cohesion value of zero and effective angle of shearing resistance ranges between 28–44 (°) (Turner et al., 2019).
Atterberg limits	Liquid limit ranges between 100–550% and Plastic limit ranges between 80–250% (Turner et al., 2019). WTR was partially dried but otherwise untreated (~ 10–40% w/w dry matter).
pH	Values vary but a significant difference in WTR pH to the applied environment can have detrimental effects on the surrounding environment (Mokonyama et al., 2017). For the range of values, see Table 4.
Nutrients	Contains four important nutrients: phosphorus, nitrogen, potassium and sulphur (Mokonyama et al., 2017). For the range of values, see Table 3.
Trace metals	Lower in WTR than WWTR. Varies in WTR depending on pre-treated water properties and treatment method but typically high in Al or Fe (Mokonyama et al., 2017), depending on coagulant used. The range of values, shown in Table 4.
Total carbon	Ranges between 127–188 (g kg^{-1}) (Dassanayake et al., 2015). Whether this is dry or wet state is not stated..
Water holding capacity	Determined as 0.37 ± 0.02 ml g^{-1} by fully saturating 100 g, allowing to drain then measuring retained water (Howells et al., 2018). In addition, gravimetric water-holding capacity was measured at 0.033 Mpa and ranged from 187 to 710 g kg^{-1}, with a median of 400 g kg^{-1} (Dayton and Basta, 2001).
Organic matter	At 6.3% when WTR were air-dried and then passed through a 2 mm sieve prior to analysis (Ippolito et al., 2009). For a range of organic matter Mokonyama et al. (2017) suggests 0.5 to 16.7% which benefit land application.

Table 3. Typical total nutrient content of WTR from the UK and Scotland.

	Dry matter content (%)	N (kg fresh t^{-1})	(P_2O_5) (kg fresh t^{-1})	(K_2O) (kg fresh t^{-1})	(SO_3) (kg fresh t^{-1})	(MgO) (kg fresh t^{-1})
UK mean values (AHDB, 2020)	25	2.4	3.4	0.4	5.5	0.8
Scotland (Earthcare, 2020)[a]	18-25	1.7-4.4	0.3-1	0.04-0.1	2.8-4.4	0.16-0.2

[a] Treatment works included: Amlaird, Auchneel, Bradan, Camps, Carron Valley, Glengap, Killiecrankie, Lintrathen, Loch Turret, Lochinvar, Pateshill and Penwhirn, Turriff and Whitehillocks.

Earthcare (2020) reported a summary of five case studies in Scotland, in addition to 18 peer-reviewed global studies on WTR total element concentrations, organic matter and pH, originally presented by Turner et al. (2019) (Table 4). The significant range of data indicates a wide variability in WTR characteristics due to varying pre-treated water characteristics and methods of treatment. Table 4 further proves that accurate identification of WTR characteristics from specific WTR should be done through direct analysis, as using existing published data as an indicator could be associated with significant error.

2.2.2 Legislation

The Waste Management Licensing (Scotland) Regulations 2011 (Scottish Statutory Instruments No. 228) is derived from the Waste Framework Directive (Council Directive 2000/60/EC (2000) and sets out that WTR is a waste, and that its use needs to be authorised, via licence exemptions.

Present legislation encompasses certain relevant aspects of this process, including legislation requirements for cross compliance and to inform good practice such as:

- The Action Programme for Nitrate Vulnerable Zones (Scotland) Regulations (Scottish Statutory Instrument, 2008, 2009), with the inclusion of The Designation of Nitrate Vulnerable Zones (Scotland) Regulations (Scottish Statutory Instrument, 2015).
- Guidance booklets (Nitrate Vulnerable Zones: guidance for farmers, Scottish Government 2016) produced for farmers to assist compliance with the Action Programme.
- The General Binding Rules (GBR) within The Water Environment (Controlled Activities) (Scotland) Amendment Regulations (CAR) 2021 (Scottish Government, 2021).
- The Water Environment (Groundwater and Priority Substances) (Scotland) Regulations 2009. Scottish Statutory Instruments 2009/42.
- Water Environment and Water Services (Scotland) Act 2003 (a consultation process for an update is being undertaken at present).
- The Environment Act (1995).
- The Waste Management Licensing (Scotland) Regulations 2011, Scottish Statutory Instruments No. 228.
- The Pollution Prevention and Control (Scotland) Regulations 2012 Scottish Statutory Instruments No. 360.

In the Scottish Water Directions 2020, Scottish Ministers have set out objectives for the period 2021 to 2027. Whilst these make no specific reference to WTR, they require the water industry to make progress towards realisation of the long-term vision, part of which is to secure a sustainable future, work within the means of the planet's resources, maximise the contribution to achieving net zero emissions and deliver the greatest possible value from resources. In addition, the Directions require Scottish Water to have regard to the Scottish Government's Circular Economy Strategy, including any updates or replacements.

One major nutrient found in WTR is nitrogen, important for plant and crop growth, however high concentrations are harmful to people and the environment. Nitrates are a major component of commercial agricultural fertilisers and have been a significant source of water pollution across Europe and elsewhere. Many European countries, including the UK, have aimed to reduce nitrate pollution, particularly in groundwaters, by regulating application of fertilisers that contain nitrogen to land.

However, there has been no overall significant reduction in groundwater nitrate contamination (European Commission, 2018/246) and agriculture remains the main source of nitrate pollution within Europe (Musacchio et al, 2020). A report published in 2018 on the UK's Progress on Reducing Nitrate Pollution stated that due to the historic overuse of artificial fertiliser, it had led to nitrate pollution in many of the UKs groundwater sources (House of Commons, 2018/656).

Schedule 3 within the amended 2009 Action Programme legislation provides the calculation of maximum nitrogen application to crops, along with the predominant soil type (SSI 2009/447; Schedule 3). Closed dates for land applications are set out in Regulation 21(SSI 2008/298) and restrictions on methods of application of slurry in Regulation 24 (SSI 2008/298; Regulation 24). Therefore, this Action Programme aims to control the timing and quantity of nitrogen applied to land. If WTR are to be applied in NVZ areas, then it is essential that analysis of the N content and its impact needs to be established.

A cross compliance set of rules to assist farmers include the Statutory Management Requirements (SMRs) and Good Agricultural and Environmental Conditions (GAEC) and it is the responsibility of the farmer to be aware of these obligations. SMR 1 (FAS, 2021) is relevant for those farmers within Nitrate Vulnerable Zones (NVZ) and states that they must prepare a Fertiliser and Manure Management plan by March 1st each year. This involves calculating and recording the total amount of nitrogen, for livestock manure of 170 kg N^{-1} ha^{-1}, and for all other manures (and these include all organic waste materials) the limit is 250 kg ha^{-1}.

Within Scotland, a Grassland Derogation of the Nitrates Directive was secured from the NVZs Action Programme (SSI 2008/298) allowing farms that meet certain conditions to apply up to 250 kg N^{-1} ha^{-1} yr^{-1}.

Table 4. Range of total element concentrations, organic matter and pH for WTR acquired from 18 peer-reviewed studies internationally presented in Turner et al. (2019) and Scottish case studies reported in Earthcare (2020), all values are reported as dry matter.

Data source	Al	Fe	P	Ca	Mn	Pb	Zn	Ni	Cu	Organic matter	
Unit	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	%	pH
Range of values obtained for key parameters from 18 peer-reviewed studies from around the world (reported in Turner et al., 2019).	6.7 – 180	1.1 – 277	0.2 – 10	0.18 – 32	0.4 – 31.6	2.5 – 69	0.12 – 246	10.9 – 60	35 – 624	5.8 – 24.5	5.12 – 8.0
Mean values obtained from tests on three samples of WTR from SW* Glenfarg treatment works in 2020 (this project).	120	4.3	1.7	3.0	0.3	4.1	40.5	11.1	34.6	52.1	6.5
Mean values obtained from SW tests on 19 samples of WTR from SW Glenfarg treatment works from 2014 to 2018.	128	N/A	0.9	N/A	N/A	< 10	60.0	11.4	33.9	N/A	6.3
Mean values obtained from SW tests on five samples of WTR from SW Whitehillocks treatment works in 2020.	N/A	N/A	0.7	N/A	N/A	≤ 13.1	31.4	≤ 6.5	14.8	N/A	5.5
Values obtained from SW tests on four samples of WTR from each of ten SW treatment works[a] in 2018 and 2019 (mean values from all samples tested).	75.6 – 222 (138)	8.4 – 15.1 (11.3)	0.2 – 18[b] (1.3)	N/A	N/A	10 - 108[c] (21)	15 – 722 (59)	6.0 – 54.4 (15)	6 – 153 (26)	N/A	4.5 – 7.1 (5.9)
Values obtained from independent tests on eight samples of WTR from seven SW treatment works[d] in 2017 to 2019 (mean values from all samples tested).	N/A	N/A	0.3 - 1.3 (0.6)	1.0 – 3.7 (2.1)	N/A	11 – 47 (30)	30 – 71 (55)	4.7 – 15.1 (11)	11 – 70 (22)	58 – 67 (62)	4.4 – 6.7 (6.0)

*SW=Scottish Water

a Treatment works included: Auchneel, Bradan, Glengap, Killiecrankie, Lintrathen, Loch Turret, Lochinvar, Penwhirn, Turriff and Whitehillocks.

b This value was highly unusual amongst the 40 batches tested and may not be a true representation of this material. Of the remaining 39 samples tested, the next highest value for P was 2.5 g kg^{-1} and the mean value of the 39 samples other than that with the abnormally high P concentration was 0.8 g kg^{-1}.

c This value was highly unusual amongst the 40 batches tested and it may not be a true representation of this material. Of the remaining 39 samples tested, the next highest value for Pb was 20.6 g kg^{-1} and the mean value of the 39 samples other than that with the abnormally high Pb concentration was 42.2 g kg^{-1}.

d Treatment works included: Amlaird, Auchneel, Bradan, Camps, Carron Valley, Pateshill and Penwhirn.

The eligibility criteria included the use of high nitrogen demand plants, soil sampling and analysis to be carried out every four years and a phosphorous fertilisation plan to be carried out for each field (Scottish Government, Accessed 30/05/21). A series of nine NVZs guidance booklets (Scotland Government, 2016) have been produced to assist framers and landowners to comply with the Action Programme for NVZs Regulations.

'Valuing Your Soils' (SRUC, 2016) supersedes PEPFAA Prevention of Environmental Pollution from Agricultural Activity (PEPFAA), (Scottish Executive, 2005). This contains a succinct summary of legal requirements in relation to the application of organic materials to land and practical guidance to farmers. The guidance includes a list of Do's and Don'ts, to enable farmers to follow legislation with requirements to maintain 'Good Agricultural and Environmental Condition' (GAEC). An assessment of risk of pollution and demonstration of land suitability (via a 'statement of agricultural benefit' or 'statement of ecological improvement') is required before the treatment can start at the stage of a new registration and for each renewal.

2.2.3 Regulation

WTR is a waste and therefore waste regulations apply to its use. Under normal circumstances the spreading of waste to land would require a Waste Management Licence (WML), but exemptions to this can be applied to certain specific spreading activities. It is a requirement that all exempt activities involving waste spreading to land are registered with SEPA.

Exempt activities are quite specific and are defined in Schedule 1 of The Waste Management Licensing (Scotland) Regulations 2011. The specific exemptions that are relevant to the application of WTR to land are paragraph 7 and paragraph 9 of Schedule 1.

- The treatment of land for agricultural benefit or ecological improvement (Paragraph 7)
- The reclamation or improvement of land (Paragraph 9)

Key aspects of the paragraph 7 exemption (WMX-TG7) to treat land for the benefit to agriculture or ecological improvement that are relevant to the spreading of WTR to agricultural land https://www.sepa.org.uk/media/105235/the-treatment-of-land-for-agricultural-benefit-or-ecological-improvement-technical-guidance-note-for-paragraph-7-exemptions.pdf) are summarised below:

1. No more than 250 t ha^{-1} of most waste types (including WTR) may be spread per year.
2. The storage limit for any paragraph 7 exemption is 1250 t.
3. The waste must not be mixed with any other material which does not itself provide benefit to agriculture or ecological improvement.
4. On initial registration of the exempt activity, specific information must be provided such as a location plan for the application activity, plan of the storage area etc. Further requirements are detailed within Paragraph 7 of Schedule 1 of the 2011 Regulations.
5. Before notification of intention to SEPA to spread WTR to land, analysis of the wastes to be spread and the receiving soil must be undertaken, as outlined in Schedules 2 and 3 of the 2011 Regulations. To supplement the information in these schedules, SEPA have produced a clearly set out list of parameters for which all wastes (including WTR) and receiving soils must be analysed to register a paragraph 7 exemption.
6. Parameters for which WTR should be analysed include pH, total nitrogen, readily available N content (RAN) and potentially toxic elements, while soil parameters that require analysis include pH, extractable major nutrients and potentially toxic elements. For specific waste materials, additional waste analysis is required.
7. If spreading WTR to land for benefit to agriculture, the following key requirements must be met:

a. The applicant must ensure nutrient addition rates planned from the spreading activity take account of the soil nutrient status and other sources of nutrient supply and be matched to the needs of the planned crop rotation.

b. Addition of total nitrogen attributable to the use of the waste on the land in any 12-month period must not exceed 250 kg ha^{-1}. As WTR generally have high nitrogen content (although WTR in Scotland typically have lower nitrogen content compared to the results WTR internationally), this requirement, as well as the total content of phosphorus and other nutrients, is likely to result in restrictions on the maximum permissible spread rate for these materials (FAS/SRUC technical notes TN715-718, 2020). If claiming that addition of organic matter from WTR spreading is a benefit, the applicant should outline how this is likely to improve the capacity of the soil to hold water, or soil porosity, stability, tilth and/or workability.

WTR can also be used under a paragraph 9(1)(b) exemption, for the reclamation or improvement of land where such treatment results in benefit to agriculture or ecological improvement. However, in order to register a paragraph 9(1)(b) exemption (WMX-TG9) to use WTR on land (https://www.sepa.org.uk/media/105209/the-reclamation-or-improvement-of-land-technical-guidance-note-for-paragraph-9-exemptions.pdf), all of the following must apply:

1. The WTR must be used for the purpose of reclamation, restoration or improvement of land which has been subject to industrial or other man-made development.
2. The waste is suitable for use for the purpose outlined in point 1, above. Note that this means that, in addition to the waste not being contaminated with substances at levels that could pose a risk to the environment and/or human health, it must also be suitable for the planned final land use, e.g., if the plan is to use WTR to restore a site and then grow trees on that site, but testing of the WTR demonstrates they are likely to have very low porosity, then they may not be suitable for use, because they could rapidly become waterlogged, impairing tree growth.
3. The WTR must be used in association with requisite planning permission.
4. Waste used under an exemption, WTR must not be placed to a depth exceeding 2 metres; this applies to the total depth of all waste materials used under the exemption, including WTR.
5. Waste volumes of WTR used under paragraph 9 must not exceed 20,000 m^3 ha^{-1}; this applies to the total volume of all waste materials used under the exemption, including WTR.

Other relevant regulations that impact on the use of WTR on agricultural land include: the Water Environment (Controlled Activities) (Scotland) Amendment (CAR) Regulations 2013 (Scottish Government, 2011b & SEPA, 2019) and the Water Environment (Miscellaneous) (Scotland) Regulations 2017 which came into force on 1st January 2018; (Scottish Statutory Instrument (SSI), 2017). SSI 2017 is relevant in that it includes the amendment to Schedule 3, the General Binding Rules (GBR), a mandatory set of rules covering 'low risk' agricultural activities that may have adverse impacts on the environment. General Binding Rule 18 (GBR 18) is relevant to WTR spreading to agricultural land and is shown in full in Appendix 1. (Appendix 1, Table A1).

GBR 18 necessitates those nutrients from any source, whether commercial fertiliser, farmyard manure/slurry, or waste materials used under paragraph 7, such as WTR, are only applied where there is a crop requirement and that the amount of each nutrient applied matches the need of the following crop. Therefore, a calculation of the nutrient budget, based on accurate soil analysis, needs to be undertaken. Contractors, agents and land managers must take into consideration all fertilisers that are applied to the land throughout the year including livestock slurry, organic and inorganic fertilisers and other amendment products to ensure that the soil is not overloaded with nutrients (excess nutrients may leach out of the soil and pollute ground and surface waters).

GBR 18 also states that organic fertiliser must not be spread on frozen, snow-covered and waterlogged ground. To assist land managers in complying with this GBR 18, SEPA is encouraging the use of nutrient management software tools which have been made available via the Planet Nutrient Management website Plant4farmers (Plant Nutrient Management, 2021). Good nutrient management is important for both farm efficiency and protection of the environment. It is important that farmers recognise and account for the contribution of nutrients in waste materials spread to land, including WTR, in nutrient budgets.

2.2.3.1 Legislation: global overview of WTR management

The application of WTR to land is increasing in some countries as reflected in practices in countries such as Australia and South Africa, and application on forestry land in the UK and USA.

Australia

As a waste product, the main legislation which guides WTR management in Australia is the Environment Protection Act 1993 (South Australia) particularly, Section 25, along with the promotion of a waste hierarchy. As an example, the Sydney Water Corporation of New South Wales, Australia stored and then reused 100% of their produced WTR via land spreading in their catchment area. In 2007-2008, 4,238 t of WTR were reused and in the period 2011-2012, 5,228 t was reported as part of their Environmental Indicators Report (Sydney Water, 2011). This level of reuse of WTR has continued and Sydney Water have developed a Resource Recovery Master Plan of which WTR are part of the Bioresource product list (Annual Environmental Performance Report 2019). It may be that Sydney Water's approach can be a benchmark for improvement in recycling WTR within Scotland and the rest of the UK.

Queensland have produced an End of Waste Code (EOW), specifically for WTR (ENEW07503318) in accordance with Section 159 of the Waste Reduction and Recycling Act 2011 which contains a suite of measures to reduce waste generation, landfill disposal and encourage recycling. It states that if an EOW code has been given for a WTR, then it becomes a resource and must meet specific requirements. If it does not meet those requirements, it becomes a waste. A registration form is required to be completed by the producer and user of the resource, copies which can be downloaded from Queensland Government website (End of Waste (EOW) framework, Queensland).

The legislation establishes a new framework to modernise waste management and resource recovery practices in Queensland. It promotes waste avoidance and reduction and encourages resource recovery and efficiency. In summary:

- Records must be kept, the generated WTR needs to be produced using a coagulation process (with the use of aluminium sulphate and/or anionic and catatonic polymers).
- It does not exceed maximum concentration limits for a variety of chemical compounds: resource quality criteria of their guidance, is listed in Table 5 below.
- Has a pH 6.5-8.5.
- The producer must sample, measure and record the composition of the resource, quarterly per year.
- The WTR suitability to become a resource is determined by an appropriately qualified person.

For the conditions of use, the resource:

- Must be applied to land as a soil ameliorant, as a soil conditioner or used for manufacturing compost.
- It must not be applied to land that contains potential acid sulphate, actual acid sulphate soils and/or has a soil pH < 5.5 or > 9.0.
- Prior to land application, an appropriately qualified person must determine the agronomic load rate after considering the resource composition, crop nutritional demand, and soil characteristics.
- The resource can only be applied at the agronomic loading rate calculated by the qualified person.
- In accordance with industry standards or guidelines.
- Records must be kept of the detailed assessment, land data and application rates.
- Resource must be stored in a way that prevents it from contacting stormwater or runoff.
- All reasonable measures must be taken to minimise or prevent environmental harm.
- Resource must not be released that is not in accordance with the EOW code.

Details of the guidance for WTR alum reuse is summarised within the investigative report by Smart Water Fund (2015) and states that 'land application of alum sludge' has a range of potential benefits. However, their case study illustrated that the addition of alum sludge was considered to have an undesirable impact on nutrient levels in agricultural soil and thus does not add value to soils. It may be of use for land application where soil phosphorous levels need to be controlled, or alternatively could be used for landfill lining and capping.

France

A Good Practice guidance document has been produced in France to promote suitable disposal and reuse of WTR, (AFNOR, 2015). This guidance aims to engage water treatment works operators to become involved in the reuse of WTR. Some suggested routes for reuse of the WTR include:

- Discharge into wastewater treatment plants where the resultant sludge is recycled to land.
- Incineration and energy recovery.
- Agronomic land spreading.
- Agronomic mineral amendment.
- Use in composting.

A suite of parameters is proposed for analysis of the receiving soil to determine its suitability for WTR

Table 5. Resource quality criteria as listed within Table 1 of the End of Waste (EOW) framework, Queensland.

Quality characteristic	Total concentration (mg kg^{-1})
pH range	6.5-8.5
Aluminium	250,000
Arsenic	100
Cadmium	1
Chromium	550
Copper	100
Lead	150
Manganese	19000
Mercury	1
Nickel	110
Selenium	5
Zinc	200
Total Organic Fluorine (TOF)	0.005

spreading. Operators need to determine other pieces of key information to guide sustainable spreading, such as the receiving plot size and planned application rate. A search was undertaken to determine if this good practice model has been implemented. No information on the extent of implementation could be found, however French waste regulations (based on the EU Waste Framework Directive) have been reinforced by the Circular Economy Roadmap issued by the Ministry of Ecology in April 2018. The focus is mainly on municipal waste with Section 37 summarising the approach to delivering an end of waste strategy.

South Africa

The relevant environmental legislation within South Africa is the National Environmental Management (NEM): Waste Amendment Act (Act 26 of 2014). Due to an abundance of regulations and the push for 'waste' to move towards reuse, recycle and recovery, many waste activities became difficult to implement, as they triggered multiple legislative requirements (Godfrey & Oelofse, 2017). The current legislation in South Africa that regulates waste management does not distinguish between water treatment residuals (WTR) and sludge from wastewater treatment works (WWTWs), as they are both considered as a waste product. This results in users requiring authorisation for their treatment and/or reuse. It has been advised by Mokonyama et al. (2017) that a streamlined approach to the authorisation of this waste stream is agreed upon by the Department of Environmental Affairs and Tourism (DEA). Despite this, land application of WTR has been a favoured management approach in South Africa, due to it beneficially modifying the soil, whilst also recycling a waste (Helserman, 2013). The most common land application uses for WTR are on agricultural land, forest land, and land reclamation (Mokonyama et al., 2017). It is likely that the 'beneficial modification of the soil' here is associated with increases in soil organic matter, which is in turn related to South Africa's climate - i.e., semi-arid/Mediterranean with low background organic matter levels in soils.

The Herselman report (2013) gives structured guidelines to assist the WTR producer to ensure that WTR is handled within the legislative framework; mitigate any potential adverse environmental effects and implement the monitoring requirements for the selected management option.

United States of America

The regulatory agency governing waste management in the USA is the Environmental Protection Agency (EPA). There are currently no regulations specifically relating to WTR, however, there is a long history of application of WTR to land. Within the USA, WTR are defined as an industrial waste by the existing Water Pollution Control Act of 1972 and listed as solid waste under Title 40 Protection of the Environment, Code of Federal Regulations (CFR) Part 257. Multiple regulations are applicable for the management of WTR and include the Clean Water Act (CWA), which governs the discharge of residuals back into a watercourse and the Criteria for Classification of Solid Waste Disposal Facilities and Practises (40 CFR Part 257); Resource Conservation and Recovery Act (1976); Comprehensive Environmental Response; Compensation and Liability Act (1980) and Clean Air Act (1970), which governs other methods of recycling and/or disposal of WTR (Helserman, 2013).

In many States of the USA, land application of WTR must be authorized. The chemical and physical WTR characteristics must follow the analytical requirements set by the State Regulations, for example, in Florida where they are the same levels as for biosolids (Florida Administrative Code, 2021). The National and State Regulations of the USA have increased the reuse of WTR for agricultural, ecological and industrial purposes (Keeley, 2014). One of the main reasons for this is the increased research into this issue (Verlicchi et al., 2000), which is ongoing through umbrella multistate research projects, for example WAAESD (2019) W4170: Beneficial Use of Residuals to Improve Soil Health and Protect Public, and Ecosystem Health.

Table 6. Resource quality criteria as listed within Table 1 of the Guidelines for the Utilisation and Disposal of Water Treatment Residues (Herselman report, 2013).

Quality characteristic	Total maximum concentration (mg kg^{-1})
Arsenic (As)	<40
Cadmium (Cd)	<40
Chromium (Cr)	<1 200
Copper (Cu)	<1 500
Lead (Pb)	<300
Mercury (Hg)	<15
Nickel (Ni)	<420
Zinc (Zn)	<2 800

New Zealand

In contrast to the above examples, information from New Zealand regarding WTR reuse onto land is limited and dated. New Zealand guidelines for WTR management were developed in 1998 for the purpose of assisting water suppliers, consultants, and stakeholders in selecting and implementing environmentally friendly methods of disposal (Mokonyama et al., 2017). The guidelines characterise the water treatment process and WTR produced including a discussion on the various options available for disposal, such as land and forestry (NZWWA, 1998).

The guidelines suggest that, as part of the assessment of the effects of land application, a description of alternative locations is provided. It is not necessary to prove that it is the "best" option but for the chosen option, the effects have been properly addressed, and detrimental effects avoided or mitigated. It also identifies that understanding the quantities and properties of WTR is fundamental to determining appropriate management. Applying WTR to forested and agricultural land is seen as an attractive option. There should also be considerations of pH, crop selection, fertiliser requirement. New Zealand does not have comprehensive legislation dedicated to the management and minimization of wastes and there is little or no data on WTR application to land.

2.2.4 Benefits and disbenefits from land application

2.2.4.1 Agriculture land

Using alum based WTR as soil amendments in agriculture has been reported to enhance nutrient recycling and improve soil physical and chemical properties (Dassanayake et al., 2015) summarised in Tables 2, 3 and 4. Table 7 summarises WTR application impact on agricultural soils, in both sole application of WTR and co-application. Appendix 3 provides further information regards combining WWTR and WTR for land application.

Physical Properties

According to Verlicchi & Masotti (2000) and Elliott et al. (1990), successful application of WTR on agricultural land requires an evaluation of their effects on soils physical

Table 7. Impact of and observation for using WTR on agricultural lands in sole and co-application.

	Impact of and observation for using WTR on agricultural land	Reference
1	Long term (7.5 years) study of effect of WTR on soil at a site in Michigan, USA which had received >10 years application of poultry manure prior to the application of WTR. As a result of the WTR application, Al-based WTR immobilized P and remained stable 7.5 years following initial land application.	Agyin-Birikorang et al. (2009)
2	Mn release from WTR from a treatment plant using $KMnO_4$ was assessed as part of the treatment process and found increased extractable Mn concentrations in soils amended with Al-WTR enriched with Mn. The authors suggested a WTR pre-screening procedure (meaning testing elements such as Mn) to determine if land application of WTR would release elements such as Mn that may cause plant growth problems.	Novak et al. (2007)
3	Effects of different combinations of WTR and biosolids (**co-application**) on two plant species in a laboratory were studied and showed that WTR reduced plant-available P to both species. No visual P deficiencies were observed.	Ippolito et al. (2002)
4	Long-term effects of WTR-biosolid co-application on P cycling in semiarid rangelands at a site in Colorado, USA is conducted. Pathway analysis shows that even after 13 years following initial **co-application**, WTR still acted as the major stable P sink. Additionally, differences in semi-arid rangeland plant and soil microbial communities were noted 12 years after WTR-biosolids co-applications as affected by biosolids treatments alone. The effects were indicative of a successional shift from a community of low nutrient availability and tight nutrient cycling, to one with more readily available resources and decreased need for symbiotic arbuscular mycorrhizal fungi associations.	Bayley et al. (2008)
5	Long-term effects of a single co-application and short-term effects of a repeated **co-application** of biosolids (10 t ha^{-1}) and Al-WTR (5, 10, 21 t ha^{-1}) on rangeland soils and plants are reported. No change in soil pH, Electrical conductivity, NO_3–N, NH_4–N, total C, or total N by WTR application was detected. However, extractable soil Mo decreased with increasing Al-WTR rate, most likely due to WTR adsorption. Mo content in the two dominant plant species decreased with repeated WTR application as compared with a single WTR application. However, Mo deficiency was not observed.	Ippolito et al. (2009)

properties (such as cohesion, aggregation, strength, and texture which affect hydraulic properties of the soil), plant growth and groundwater quality. Accordingly, consideration of all the above-mentioned factors before using WTR for agricultural land application is required. For most agricultural soils, particularly those under arable cropping, increasing soil organic matter (SOM) content has a range of benefits such as increased crop yields, and lowered additional nutrient input requirements. Increasing organic matter content in soil also improves soil structure which results in better water infiltration and hence improved drainage. Land application of alum based WTR could improve soil air and water holding capacity (Lin and Green, 1987) which results in better root system performance which is required in agricultural soils.

WTR can contain fine grained size particles such as clay (Howells et al., 2018) which if added to agricultural fields with fine particles could potentially reduce soil porosity and lead to flooding risk, but could also be beneficial, increasing nutrient and water retention, if added to a sandy soil. Accordingly, to avoid WTR disbenefiting agricultural soils, the WTR and agricultural soil's particle size distribution should be analysed prior to the application to ensure that the WTR is being spread in a suitable location.

Chemical Properties

The nutrients provided by WTR are presented in Table 3. According to Table 4, WTR pH ranges between 4.4-8. Maintaining soil pH at optimal levels, generally done in farming via the application of lime directly, has many well documented benefits such as increasing microbial activity and maximising the availability of macronutrients N, P and K (Teagasc, 2021). Higher pH soils can be prone to deficiency in trace nutrient availability to crops, particularly if soil pH is >7.5. In soils in Scotland, trace elements, particularly manganese for cereals and cobalt for livestock, deficiency can be induced by pH values of >6.3, the severity depending on soil texture (A. Sinclair, pers. comm. 2022). Therefore, it is important to determine both WTR and soil pH before spreading a WTR to land. Sheppard and Floate (1984) showed that growth of ryegrass roots was reduced as the soluble Al concentration increased in four Scottish brown earth soils at pH 3.5 - 4.9. Accordingly, the impact of applying Al-based WTR to agricultural land on 'below ground' biomass should be considered. In SRUC Technical Note TN714 liming materials and recommendations, Crooks et al. (2019) state that at soil pH values below 5.6 in mineral soils in Scotland (independent to application of WTR), soluble aluminium inhibits root growths and reduces yields. Accordingly, WTR application could potentially exacerbate the Al toxicity under such conditions. Soil chemical properties play a key role in determining WTR application rates. The variability in the published WTR data shown in Table 4 indicates the importance of identifying the characteristics of specific WTR, as referring to existing data may be associated with significant error. Aluminium content in WTR and their provision of nutrients such as potassium and sulphur should be considered in respect to the receiving soil chemical properties.

Several studies have reported benefits of adding WTR to other types of fertilisers for plant growing purposes such as mixing vermicompost (Ibrahim et al., 2015) or poultry litter (Dayton et al., 2003) with WTR. Ibrahim et al. (2015) realised improvement of saline sodic soil physical properties and wheat yield as a result of combining vermicompost with WTR. The authors also reported that the mixing with vermicompost improves WTR efficiency in ameliorating the soil physical properties, especially in salt affected soils (although not common occurrence in Scotland) to improve the yield of wheat. Dayton et al. (2003) realised that applying WTR at the rate of 50,000 kg/ha (50 t/ha) to box plots treated with 16,700 kg/ha (16.7 t/ha) poultry litter reduced runoff P by 14.0 to 84.9%.

According to Mokonyama et al. (2017), adding WTR to poultry litter results in reduction of water-soluble P up to 87% depending on the dose and incubation period. Turner et al. (2019) reported benefits from using WTR for agricultural production in areas that have contaminated soils requiring management and remediation.

2.2.4.2 Forestry

Forestry and land restoration are closely linked as WTR, and other types of waste materials, are used in the land remediation of former open cast lands to develop soil properties to a state fit for woodland creation. Table 8 summarises previous research into WTR application impact on forests. Remediated land is frequently planted to woodland. Ecosystems provide living spaces for plants or animals; they also maintain a diversity of different breeds of plants and animals' (TEEB, 2010). Various definitions of supporting ecosystem services exist; two of the most cited definitions are 'supporting services underpin almost all other services' and 'supporting services are those that are necessary to produce all other ecosystem services'. They differ from provisioning, regulating, and cultural services in that their impacts on people are often indirect or occur over a very long time, whereas changes in the other categories have relatively direct and short-term impacts on people (Millennium Ecosystem Assessment, 2005). Examples of supporting services required in forestry include soil formation, nutrient cycling and water cycling.

In forestry application, consideration of existing soil properties (pH, soil nutrients, organic matter etc.) is required. These properties play an important role in

Table 8. Impact of and recommendation for using WTR on forest creation.		
	Impact of and recommendation for using WTR on forest creation	**Reference**
1	Limited application of Al-based WTR to forest soil in USA at the application rate of 1170 m^3 ha^{-1} showed the phosphate cycle and forest growth pattern were not affected.	Robert and Edward (1987)
2	Application of Al-based and polymer WTR to forest soils at the application rate of 0.8 to 2.5 g kg^{-1} (equivalent to approximately 3.2 to 9.9 t ha^{-1} assuming a bulk density of 1.33 g cm^{-3} and an application depth of 0.3m) showed no effect on growth or nutrient content after at least 1 year.	Bugbee and Frink (1985) Novak et al. (1995) Dayton and Basta (2001)
3	Application of solid Al-based WTR to forestry lands at the application rate of up to 2.5% by dry weight of the topsoil in USA showed no adverse effects. It was concluded that the WTR can be applied at high rates with no detrimental impact on the soil, groundwater or tree growth up to 30 months after application.	Geertsema et al. (1994)

the requirement of WTR and application rate. In land restoration, due to poor quality of soil, application of WTR would provide benefit to the soil properties discussed above. These applications are discussed further in the next section.

2.2.4.3 Land restoration

This section focuses on land restoration for soil creation and Table 9 summarises WTR application impact on land restoration. Restoration sites predominately lack topsoil, suffer compaction and provision of sufficient nutrients and organic matter is crucial. Accordingly, in restoration sites, inputs of organic matter which could be provided by WTR will help to create good soil structure, reducing erosion of soil via wind and water.

Due to high organic matter content in WTR, the material has a great potential to be used for landscaping and development of nutrient rich topsoil. However, it is suggested by the author that WTR should be combined with other types of fertilisers to benefit restoration efforts (Mokonyama et al., 2017). Although no further information was provided by Mokonyama et al. (2017) on why co-application of WTR with other types of fertilisers would benefit restoration efforts, authors of this report believe that co-application could improve qualities that WTR cannot solely provide (e.g., adjusting land pH) which co-application with lime could provide.

Depending on WTR and land pH values, WTR could be used to neutralise highly acidic or alkaline soils (although co-application with lime might be required), which occur more frequently in areas requiring land restoration.

WTR have a range of particle size distributions, depending on the input and treatment process, leading to high fine particle content of some WTR. It is of major importance to analyse flooding vulnerability of restoration projects prior to WTR application to avoid flooding events as fine particles from WTR could result in clogging of soil pore spaces and hence reduce drainage.

2.2.5 Field and lab trial application rates for spreading in agriculture and forestry

In an experimental plot in Australia, Ahmed et al. (1998) applied Al based WTR (in dry state) to ryegrass plots at the rate of 0, 200, 400, 800 and 1600 t ha^{-1} with lime at the rate of 0, 1.8, 3.6, 7.2 and 14.4 t ha^{-1}. The mixing of WTR and lime with soil was done in a laboratory incubation experiment. At all application rates, the authors realised positive impacts on soil physical properties, including reduced dry bulk density and increased porosity and infiltration rate. However, they didn't observe visible impact on plant growth or yield, even at the highest rate of application.

In the USA, Oladeji et al. (2007) studied application of Al based WTR to P-deficient bahiagrass (*Paspalum notatum*) plots at rates equivalent to 0, 10, and 25 g kg^{-1} (oven dry basis) with four P sources at two application rates. These application rates correlate to approximately 0, 40 and 100 t ha^{-1} assuming a bulk density of 1.33 g cm^{-3}

Table 9. Impact of and recommendation for using WTR on land restoration.		
	Impact of and recommendation for using WTR on land restoration	**Reference**
1	WTR application potential for land restoration was evaluated in USA. Analysis of WTR samples showed all the samples were suitable as soil substitute based on plant nutrients, with the exception of P. For crop growth tomato vegetative yield and tissue P were poor. This was linked to phytotoxic nitrite-nitrogen (NO_2–N) (>10 mg kg^{-1}) generated during the bioassay or because of WTR P deficiency.	Dayton and Basta (2001)
2	WTR was combined with vermicompost in Egypt to improve WTR efficiency in ameliorating the soil physical properties. It was concluded that WTR can be used as an ameliorating material for the reclamation of salt affected soils.	Ibrahim et al. (2015)

and an application depth of 0.3 m. The authors realised an increase in P storage capacity with the application rate of WTR, with the degree of increase varying with sources of P acquired from conventional fertilisers such as manure and biosolids. The study reported an increase in soil soluble P concentrations as soil P storage capacity was reduced, and a change point was identified at 0 mg kg^{-1} soil P storage capacity in the glasshouse and field studies (Oladeji et al., 2007). The authors identified a change point in the bahiagrass yield at a tissue P concentration of 2 g kg^{-1}, corresponding to zero soil P storage capacity (considered as an agronomic threshold above which yield and P concentrations of plants declined and below which there is little or no yield response to increased plant P concentrations). Silveira et al. (2013) also investigated application of Al based WTR to bahiagrass plots at the rate of 0, 35 and 70 t ha^{-1}. The authors realised a reduction in grass yield in the first year, when the WTR was applied at the highest rate, which is believed to be due to disturbance of the bahiagrass stand, by disking for the amendment incorporation, and not to the effects of the Al-WTR. Gallimore et al. (1999) evaluated the use of two Al based WTR with an application rate of up to 45 t ha^{-1} combined with 6.7 t ha^{-1} of poultry litter to grass pasture. The authors realised a reduction in mean dissolved P as a result of the WTR application, compared to dissolved P pre-WTR application, resulting from P fixation and reported no adverse effect on grass yields.

In a six-year study, Agyin-Birikorang et al. (2009), investigated two trial fields that received 0 or 114 t ha^{-1} dry Al based WTR and realised a reduction in dissolved P and bioavailable P by >50% as compared to the control plots. The authors reported no negative impact on crop yields.

In the USA, Bayley et al. (2008) and Ippolito et al. (2009) investigated the application of three different Al-WTR (at 5, 10, and 21 t ha^{-1}) co-applied with a single biosolids application (rate 10 t ha^{-1}) to a loamy soil pasture (shortgrass prairie with animals excluded). Bayley et al. (2008) realised the significant capacity of WTR as a stable sink for P when mixed with biosolids. Madison et al. (2009) and Judy et al. (2019) reported Al-WTR was applied to a pasture at a cumulative rate of 78 metric t ha^{-1} over two years, and researchers evaluated the effects of dietary Al from the Al-WTR on cattle over two years (Madison et al., 2009). Results showed that Al-WTR had no adverse effects on growth, development, or blood plasma mineral concentration of the cattle, likely due to low Al availability from Al-WTR. WTR application did not adversely affect forage mineral concentrations. The researchers concluded that Al-WTR is safe and could be applied to pastures at low to moderately high rates (=78 metric tons ha^{-1}) to help reduce P runoff and leaching as investigated in the study (Madison et al., 2009).

Compared with studies of WTR spreading on agricultural land, comparatively few studies of WTR spreading at different rates for forestry land could be found. In one study, Geertsema et al. (1994), working in the USA, applied Al based WTR to forestry plots (with original soil pH=4.8) at the rate of 2.5% by dry weight in the topsoil (or 1,100 t ha^{-1}, assuming a bulk density of 1.33 g cm^{-3} and an application depth of 0.3 m). They concluded that there was no detrimental impact on the soil, groundwater, or tree growth up to 30 months after application.

Besides the studies that are discussed in this section, no further information was found on impact of long-term use of WTR on land. It appears that routine monitoring of soil properties and crop/tree growth is either not widely carried out at WTR spreading sites and/or data from such monitoring has not been widely reported, leading to limited knowledge of the long-term benefits/impacts of WTR use on both agricultural and forestry land.

2.2.6 Potential P immobilisation issues caused by WTR

Phosphorus exists in the soil within organic material, occluded in hydroxides and as phosphate salts formed from rock weathering. Available quantities are usually low, and farmers may apply phosphorus fertilisers. Overapplication of P to soil can result in accumulation, with the associated risk of release under specific conditions and resultant transport to water bodies leading to eutrophication. A major process involved in this release is soil transport through erosion, although surface water runoff and leaching also play a part.

In Scotland, leaching of P is less likely than in other parts of the world, where the impacts of WTR spreading have been researched, as significant P fixation by Al occurs at pH values below 6. According to SRUC Technical Guidance Note TN714 (Crooks et al., 2019), 64% of arable and grassland soils in Scotland have a soil pH of 5.5-6.25, with 20.3% above and 16.1% below this range. Erosion and runoff are therefore more likely mechanisms for P transport to streams and water bodies associated with WTR spreading to land in Scotland. Lateral flow transport of dissolved P through soil is also a risk if there is heavy rainfall soon after WTR application.

There is concern that WTR may immobilise P that is already within soils; if this does occur (through processes including fixation on hydro(oxides) that are present in high concentration in WTR), then it would likely exacerbate the existing Al-based immobilisation at low pH values, resulting in further reduced available P.

There are no references in the literature containing all four key phrases ‘phosphorus immobilisation’, ‘soil’, ‘sludge’, ‘Scotland’. However, removing ‘Scotland’ from this search reveals 92 publications on Web of Science. Of these 92, many relate to sewage sludge and only 7 were considered relevant with a focus on the topic of concern (WTR) under comparable climatic conditions. There were also several publications that focussed on the potential use of sludge-derived biochar and other products for immobilisation of contaminants including heavy metals and elements such as Cu, Zn, P and S, if present at levels high enough to become toxic (e.g., in soils containing mining residue). While not directly relevant to the topic of concern, they do highlight and reinforce the message that WTR have the potential to immobilise soil nutrients important for plant growth.

Furthermore, most of the work on potential P immobilisation involved sewage sludge, rather than WTR, and was focussed on ways to immobilise P in the sewage sludge to control release of available P. There was no information found on how the different characteristics of these two types of sludge would influence potential P immobilisation.

Turner et al. (2019) highlighted the potential of WTR for the immobilisation of 'excess' nutrients in soil. They also pointed out that application onto 'clean' land is well-established in the UK and USA, and that a reduction in plant-available P has been observed following application (as well as reduced plant P concentrations). It is possible that this has occurred through immobilisation of P in soil depending on the organic matter and Al and Fe content of the wastewater treatment residue, but it may also be caused by high nitrogen and comparatively low phosphate concentrations in wastewater treatment residues that are used as fertilisers. The wastewater treatment residue in these circumstances may provide enough nitrogen to support crop growth, but not enough P, which could lead to crops using up available P in soil and, over time, a decline in soil available P concentration and ultimately a decline in P in plant tissues (A. Cundill, pers. comm. 2021). The Turner et al. (2019) review is probably the most comprehensive and extensive review relevant to this topic of P immobilisation and provides specific values on composition, application rates and observed impacts (Tables 2, 5, 9 and Section 5.4 in Turner et al. (2019)). It also describes the impacts of co-application of P fertilisers as an approach to reducing the P-immobilisation effects of WTR application.

Zhao et al. (2018) reviewed evidence of the impact of Al-based WTR and determined that at pH values above 5, Al toxicity is unlikely. However, these higher pH levels are where Al-based immobilisation of P is less likely, highlighting that pH testing of soil prior to application may be necessary to allow for calculation of appropriate matching of application rates and residue chemical composition. WTR application can induce P deficiency in crops (Ipplito et al., 2011). Lombi et al. (2010) demonstrated reductions in plant growth (*Lactuca sativa*) caused by application-induced P deficiency, to both acidic and neutral soils following WTR application.

Vasilyev et al. (2020) found that application of WTR to loamy brown earth soil decreased the nutritional content (K, starch) of potatoes grown in that soil, due to immobilisation of potassium, while at the same time the soil nutrient (organic matter, total P, total K) content increased. These effects appear to have been due to variations caused in soil chemical stoichiometry by the sludge application. Tay et al. (2017) found no impact on plant growth from P availability in an experimental application coupled with P fertiliser, while at the same time demonstrating reduced Cd and As concentrations.

Adding WTR to green waste compost feedstock resulted in decreased CO_2 release, with this effect being reversed for biosolid compost (Haynes & Zhou, 2015). These effects were attributed to the reduction of available P and heavy metals, with the initial values of P in green waste compost being appropriate for microbial decomposition of organic matter but being at toxically high heavy metal levels in biosolid compost. The P immobilisation effect of WTR therefore needs to be considered in the context of existing concentrations of P in the material to which it is being applied.

2.3 Conclusions

The literature review has explored the benefits and disbenefits of WTR applications to land to agriculture, forestry, land restoration. Where information was available, discussion of other benefits and disbenefits (for soil water, water quality and ecology) was integrated into the main sections of the review above. Human health benefits and disbenefits could not be considered due to a lack of available literature. Benefits and disbenefits for the circular economy and any other environmental issues are included in Appendix 2.

WTR contain nutrients such as N, P, K, S and Mg (content varies depending on pre-treated water characteristics and method of treatment) and organic matter, which is important for maintaining a healthy soil structure, providing a slow-release store of nutrients, and allowing soils to retain moisture. Potential benefits of applying WTR to land include increasing aeration, providing sufficient N for plant growth, and increasing soil hydraulic conductivity. Further data on readily available nitrogen content (RAN) in WTR is required to assess their impact on plant yield. Excessive P sorption, which may lead to a requirement for compensatory application of P from other sources is the main disbenefit of applying WTR to land reported in literature (example of Scottish data are provided in Table 4). Concerns have also been raised regarding the leaching of metals (particularly Al) from WTR to groundwater however, laboratory and in-situ investigations have found no evidence to support these claims. High variability in the published data for WTR characteristics imply that specific analysis of

WTR is necessary for accurate risk assessment.

Impacts of applying WTR to land have been investigated internationally in countries such as USA, Australia, South Africa, France and, to a lesser extent, New Zealand. The investigations have mainly been conducted on trial plots and WTR have been used alone or together with fertilisers such as vermicompost and poultry litter. However, the dry matter content of 18-25% (Earthcare 2020) shows that WTR may be spreadable on land without the requirement to be mixed. WTR use predominately resulted in improvement in soil physical properties, increasing water retention, porosity, hydraulic conductivity, and P storage capacity, with no negative impacts on groundwater found. No noticeable improvements in plant yield were observed as a result of WTR application to land which is not unexpected since large responses in yield would only be predictable where the soil P and K status are low. An overview of benefits and disbenefits drawn from literature is shown in Table 10.

Although WTR have been proven to have the potential to improve soil physical and chemical properties and provide nutrients, which should in turn improve plant growth, the following points need to be considered for applying the material to lands:

- Accurate analysis of WTR physical and chemical properties (such as particle size distribution, pH, nutrient content) from each treatment plant is required as concentrations will vary depending on factors such as quality of pre-treated water and the treatment method (see Appendix 6).
- Accurate analysis of receiving soils. Soil nutrient concentrations and pH, in particular, are likely to govern whether or not spreading WTR from a specific source is likely to result in agricultural benefit.
- Overall cost of delivering WTR to a specific are of land in comparison to conventional fertilisers.

There is a wide variation within the regulatory frameworks of other countries in how WTR are considered as a waste product and therefore how they are ultimately treated and/or reused. Some countries such as South Africa can have multiple regulations which has seen a hindrance to WTR reuse, specifically to its application to land. South Africa use other countries' regulations and guidance as benchmarks and there is some robust documentation and research into WTR use on land in South Africa. The USA also has a series of regulations controlling waste spreading to land, but this is not specific to WTR, with states differing in their approach to regulating this waste material. By contrast, in New Zealand guidance on WTR use is outdated and little research into its benefits/disbenefits has taken place. However, Australia has had great success with recycling WTR to land, particularly in South Australia, where there is near 100% recycling of WTR, WTR are generally referred to by the positive term 'Bioresource' and are used as part of a Resource Recovery Master Plan. The End of Waste Code (EOW) specifically

Table 10. Overview of benefits and disbenefits of WTR

Benefits of applying WTR to lands are:	Disbenefits of applying WTR to lands are:
• Improving hydraulic conductivity. • Increasing P storage capacity. • Increasing porosity. • Providing nutrient elements such as P, K, N, S and Mg. • Improving soil physicochemical properties (i.e., pH, electrical conductivity, water holding capacity, cation exchange capacity, organic matter content and soil aeration). • Controlling runoff pollution and/or phytotoxicity of heavy metals. • Absorbing organic and inorganic pollutants (though not well understood). • Enhancing nutrient recycling in agricultural soils. • Better performance of plant root system due to improvement in soil air and water holding capacity. • The benefit from WTR application to land can be enhanced if a separate vermicompost or poultry litter application is also made. • Successful application for land restoration.	• Unsuitable for soils with pH < 5.5, due to high Al content and increasing toxicity of Al at lower soil pH. • Available phosphorous must be assessed, taking into account sorption capacity index of soils. • May require additional application of traditional fertilisers, such as animal manure, to negate crop yield reduction where soil is deficient in N, K, P. • Containing levels of NO_2-N which are toxic to germination of some seeds, e.g., tomato. • Some WTR Contain high levels of fine particles, therefore are unsuitable for agricultural land spreading where fine-textured soils are present as this would reduce soil porosity. • Commonly require dewatering prior to transportation which is associated with additional carbon emissions. If transported without de-watering, the transportation is associated with extra carbon footprint due to larger load carrying operation. • May not contain sufficient/right balance of nutrients to support good crop growth.

for water treatment residuals (ENEW07503318) lays out that if an EOW code has been given for a WTR, then it becomes a resource when its use is approved by the EOW. It may be that Australia's approach to WTR recovery can be a benchmark for improvement in this within the UK.

3 Technical requirements and management

3.1 Application rates and technical requirements

Spreading WTR on agricultural land is commonly done using conventional manure spreaders. However, for land restoration WTR is usually dug into the surface layer of de-compacted soil using an excavator. The reported application rates from experimental studies, discussed in Section 2.2.5, are largely reported from small scale experimental studies rather than large scale agricultural and land restoration experiments. However, for agricultural purposes WTR application rate of 50-150 t ha^{-1} has predominately been recommended in published literature. In England and Wales, application rates for agriculture are typically in the range of 20 – 60 t ha^{-1} (Earthcare, 2020). The maximum application rate permitted is 250 t ha^{-1} with a further limit on liquid applications of 50 m^3 ha^{-1} at any one time, and additionally no more than 250 kg N ha^{-1} may be applied to land (Waste Management Licensing (Scotland) Regulations 2011). Application rates have been explored through an example developed with Scottish Environmental Protection Agency (SEPA) using WTR results from a Scottish Water WTW as shown in Table 11.

Agriculture

The application rate is determined by the WTR characteristics and the nutrient requirement of the planned crop and the frequency of application. In agriculture, application is anticipated to be on an annual basis. One of N, P or PTE usually limits application rate; the maximum application rate will be determined by the requirement to avoid excessive supply of N or accumulation of P or PTE in soil to excessive levels. Table 11 shows that in these examples N limits application rate for spring barley, while P limits application rate for 2 cut silage grass. Annual WTR application rates will be in a range of 50-150 t ha^{-1} for agricultural use. Note, total N and P content may not necessarily provide sufficient N or P for crop growth due to nutrient losses (Farm Advisory Service, 2019). Also, the application of WTR cannot satisfy the K need of the crops.

Land Restoration

In example 3 (Table 11), restoration, there is no N limit set in the legislation in Scotland. However, a theoretical application rate of 588 t ha^{-1} WTR provides 1000 kg ha^{-1} N. The maximum addition rate of 1000 kg ha^{-1} N is listed in the 'Key principles for the remediation of former opencast coal sites for woodland establishment, v7.2' (FLS, 2021). Nitrogen can be added at rates up to this maximum, under the condition that Potentially Toxic Element (PTE) concentrations in soil will not exceed the maximum limits set out in the soil table in the Sludge (Use in Agriculture) Regulations 1989. As can be seen from the table, spreading 588 kg ha^{-1} WTR would not satisfy the need for P_2O_5 (for this 1280 t ha^{-1} would be required). Spreading WTR at 588 kg ha^{-1} provides sufficient N, but insufficient organic matter P and K.

For restoration sites, it should be noted that the WTR (if used) is generally mixed with WWTR, which will provide the bulk of the nutrients. The numbers provided here are theoretical and based purely on calculations of need. They do not consider any limitation in P availability from the WTR or its effect on P provision from WWTR. It is considered that the addition of stable organic matter from WTR would be beneficial to ensure long-term availability of nutrients. However, reduced P plant-availability (even

Table 11. Application rate example using WTR results from a Scottish Water WTW (bold application rate show the limiting element)

Exemplar		1: Spring barley		2: 2-cut silage grassland		3: Restoration of sites with no nutrients and organic matter to achieve 20 cm soil depth		
	WTR Exemplar Results	Need in kg ha^{-1}	Application rate t ha^{-1}	Need in kg ha^{-1}	Application rate t ha^{-1}	Minimum standard	Need in kg ha^{-1}	Application rate t ha^{-1}
organic matter (kg/t)	127	n/a		n/a		8%	208000	1638
total N (kg/t)	1.7	**130**	**76.47**	210	123.53		**1000**	**588**
total P_2O_5 (kg/t)	0.5	50	100	**59**	**118**	16mg/l	640	1280
total K_2O (kg/t)	0.1	52	520	210	2100	121mg/l	970	9700

though there was sufficient total P when applied) gives rise to the potential that the application of WTR with WWTR could result in insufficient P being available. More work is required to understand these relationships in the Scottish context and is part of recommended future work presented in Section 5.

3.2 Management

The Florida Department of Environmental Protection (FDEP 2021) provides guidance on management and handling of WTR. These are considered along with biosolids, where these must not be stored, stockpiled, or staged for more than seven days, unless stored in accordance with a NMP (Nutrient Management Plan) at an approved storage location that meets a 400 m setback from a building occupied by the public. Storage must be in accordance with the NMP and cannot cause or contribute to runoff, objectionable odours, or vector attraction.

Episodic rainfall events are a potential mechanism by which WTR may be incorporated into runoff from farmland into drinking water supplies. This risk appears to be low under normal rainfall conditions (Clarke et al., 2016), but climate change-induced unseasonal extreme rainfall events may present a mechanism for this to become a problem in the future. However, any surface-spread waste can become a problem for runoff into watercourses if spread in the wrong conditions (e.g., on top of snow or just before heavy rainfall).

The risk of soluble compounds, present in or mobilised from WTR, leaching into groundwater varies with climate conditions, increasing with temperature and precipitation (Ozdemir & Piskin, 2012). Samie & Ntekele (2014) found that levels of the parasite Giardia in WTR, produced under certain treatment processes, could be high enough to generate a health risk if the WTR contaminated water supplies. For surface waters used for recreation or domestic water supply, the risk assessment for contamination with pathogens should rely less on indicator species measurements and more on calculated probabilities of infection risk (Mraz et al., 2021).

Under a paragraph 7 exemption as outlined in Section 2.2.3 above, record keeping, reporting, and monitoring evaluation are key management activities that are required to demonstrate compliance with regulations. The maintenance of delivery records for WTR will require to be maintained along with WTR application logs and records. In Florida, other records demonstrate compliance with the site nutrient management plan including crop plantings, harvesting and applications of any other sources of nutrients. Appropriate site monitoring (soil testing and ground water monitoring) is required alongside soil fertility testing conducted at the frequency specified in the NMP. Annual soil pH testing of each application zone must be conducted to ensure the pH is at least 5 or greater (FDEP, 2019).

Scottish Water's handling, storage and transportation of WTR will have specific considerations that should be risk assessed. It is likely that Scottish Water would adopt processes to handle, transport, store and apply WTR that are similar to those already in place for managing biosolids. These are based on risk assessments and meet SEPA's expectations/guidance.

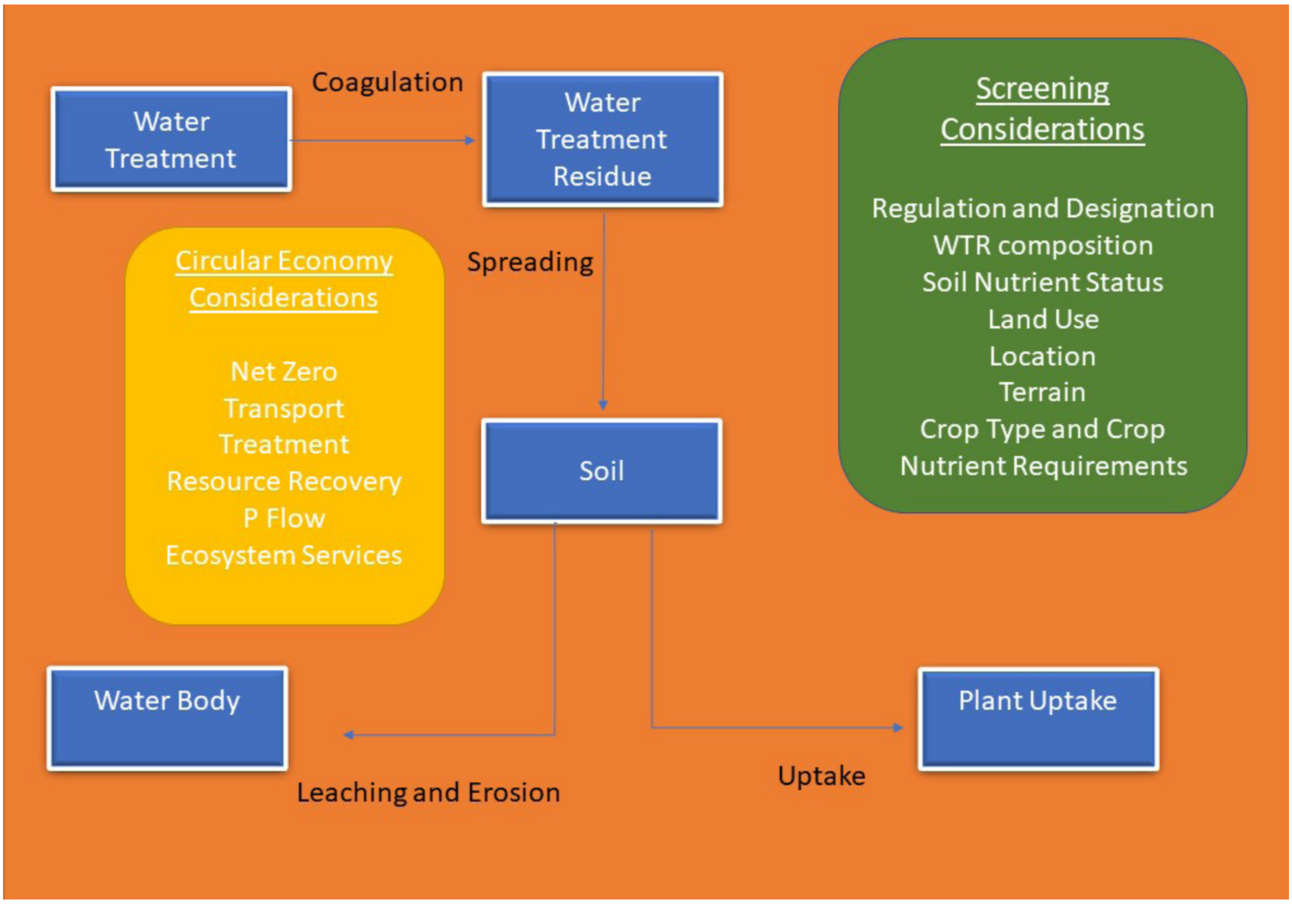
4 Decision Support Tool

4.1 Purpose and boundary of Decision Support Tool

The Decision Support Tool will support Scottish Water, SEPA and FLS to explore the application to land of WTR, encourage the consideration of additional benefits to the circular economy from spreading WTR to land and further understanding of the benefits of this for soil physical properties. The Decision Support Tool is designed as a screening tool only, as soil analysis data and specific crop nutrient requirements need to be taken into consideration when determining the application rate for a specific location. The Decision Support Tool is in Microsoft excel format and described in Appendix 5.

The boundary of the Decision Support Tool is shown in Figure 1.

Figure 1. Decision Support Tool Boundary



4.2 Key considerations in the screening process

The findings from the literature review suggest that there should be an initial screening process to inform the potential recycling of WTR to land. The findings that form the basis of the key considerations to be included in the screening process are summarised in Table 12, below.

In applying WTR to land it is important to consider the physical and chemical properties of both the WTR and the receiving soil. Benefits to the receiving soil properties and the impacts of applying WTR on the existing soil properties summarised in Table 13, below. These benefits and improvements in soil properties are summarised from the literature review. Appendix 6 lists soil and WTR testing parameters that should be tested before application of WTR to soil.

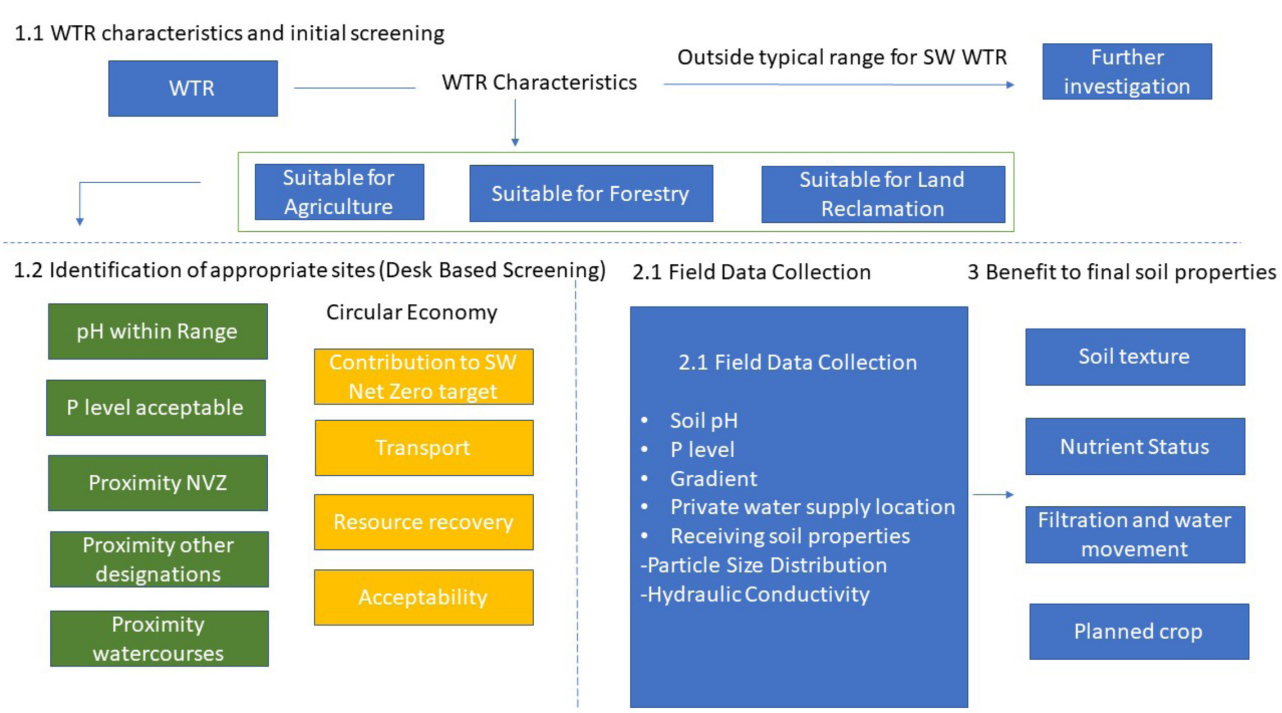
Table 12. Key considerations in screening process		
	Description	**References**
pH	In England and Wales, the application of Al WTR is limited to soils with pH above 6 due to the increased mobility of Al below pH 5 in soils, while Fe WTR are limited to application to soils above a pH of 5.	Earthcare (2020),
	Application of WTR to soils with pH<5.5 should be avoided, given the potential for the Al in the WTR to become soluble and toxic to plants. Before the application, properties of WTR and receiving land (e.g., particle size distribution, pH, nutrition values and organic content) should be analysed to evaluate suitability of using WTR for the specific application.	Turner et al., (2019)
P fixing	WTR may immobilise P that is already within soils; if this does occur, then it would likely exacerbate the existing Al-based immobilisation at low pH values, resulting in further reductions in available P.	Turner et al., (2019), Zhao et al., (2019)
	Excessive WTR application can induce P deficiency in crops.	Ipplito et al., (2011)
	WTR application can result in reductions in plant growth (i.e., *Lactuca sativa*) caused by application-induced P deficiency, in both acidic and neutral soils.	Lombi et al. (2010)
Application rates	The application rate is linked to the requirements of the receiving soil. Application rates in England and Wales are typically in the range 20 – 60 t ha^{-1}.	Earthcare (2020)
	In Scotland, maximum application rates could vary between 50 – 150 t ha^{-1} based on limiting factors such as N, P or PTE content.	SEPA communications

Table 13. Impacts of applying WTR on the existing soil properties		
Receiving soil properties	**Description**	**References**
Particle size distribution	Particle size distribution of both the receiving soil and WTR should be analysed to ensure particle size suitability for the chosen application. Some WTR contain high percentages of fine particles so if flooding is a concern, it may not be appropriate to apply fine-grained WTR to land which will reduce hydraulic conductivity. If water retention is an issue, i.e., the receiving soil is sandy, then WTR application will result in an increase in water retention.	Howells et al. (2018)
pH	WWTR pH ranges from 4.4 – 8. Maintaining soil pH at optimal levels has important benefits including increasing microbial activity in soils and maximising the availability of macronutrients N, P and K. Higher pH soils can be prone to deficiencies in trace elements and therefore it is important to know the pH level of both the WTR and receiving soil to ensure pH of the receiving soil is maintained at optimum levels.	Turner et al. (2019)
	In Scotland, the pH of many agricultural soils is below 5.5. Aluminium solubility increases as soil pH decreases and below pH 5.5, aluminium solubility may inhibit root growth and reduce crop yields. Therefore, the application of WTR could potentially exacerbate the Al toxicity, depending on its pH and the pH of the receiving soil.	Crooks et al. (2019)
Phosphorus	WTR have effectively been used to reduce phosphorus concentrations in surface water runoff from agricultural land.	Gallimore et al. (1999), Dayton et al. (2003)
	WTR application has reduced losses of phosphorus to surface and groundwater when added to Florida spodosols in a plot experiment, with co-application of WTR and other materials that contain high levels of available P.	Agyin-Birikorang et al. (2009)
Organic Matter	WTR application/s may increase soil organic matter content in locations where soil organic matter has become depleted over time. Increased soil organic matter content has a range of benefits such as increased agricultural productivity, good drainage and low additional nutrient input requirements as well as resulting in a better root system. Good soil structure is linked to a reduction in soil compaction and an increase in porosity.	Dassanayake et al. (2015), Lin & Green (1987)
	Introducing vermicompost with WTR application can increase the WTR efficiency in improving soil properties.	Dayton et al. (2003)

4.3 Structure of the Decision Support Tool

The Decision Support Tool has a 3-stage structure and is shown in Figure 2.

Figure 2. Decision Support Tool Structure



4.3.1 Stage 1 WTR characteristics and initial screening

Stage 1.1: Stage 1.1 allows the WTR from a water treatment works (WTW) to be compared with an expected range arising from Scottish WTWs, and previous results from the individual WTW, across a range of characteristics. The tool automatically flags any parameters out with the expected range.

Stage 1.2: Identification of appropriate sites. This initial, desk-based, screening stage will use existing mapping data to help determine appropriate areas of Scotland's soils. Appropriateness will be based on key screening criteria and analysis of additional circular economy benefits. The screening criteria were developed based on the results of literature review and considerations expressed by the project steering group, where green coloured text boxes represent physical criteria and gold boxes show circular economy criteria (Figure 2).

The first step in the screening stage is the identification of farmer, landowner or restoration site willingness to accept WTR for spreading to land. It is anticipated that Stage 1.2 may only be needed when first establishing potential locations for a WTR arising from SW WTW as it will exclude less preferable locations for spreading, saving the time and cost required for site-based data collection.

4.3.2 Stage 2 Field data collection

Stage 2.1: Field data collection. This stage identifies information required to be collected on site and describes the method of data collection. Following field data entry, the tool will identify, based on two key considerations of pH and P level, whether it is likely that WTR can be applied at this location. Assuming pH and P level are acceptable, then other site considerations are also stated which should then be considered.

4.3.3 Stage 3 Benefit to final soil properties

Stage 3.1: This stage identifies the benefit of adding WTR to different land uses. The benefits are similar for each land use type, but the application rate and timescale for benefits are different.

Stage 3.2: This stage calculates the maximum application rate for the WTR data entered in Stage 1. It references the need for nutrients for 2 crop types and land restoration to 20 cm.

The Decision Support Tool is a screening tool only. In this respect, it can estimate what is likely to be a maximum suitable spread rate based on the WTR. This tool cannot provide the expertise of an agriculture adviser, given that there are more land uses and recent soil analysis data to be considered when determining the application rate for a certain field.

As part of the paragraph 7 exemption application, an agricultural advisor should be engaged to determine application rate.

5 Conclusions and recommendations

This project evaluates the opportunities and implications of applying WTR to land and associated circular economy benefit, based on a synthesis of international literature. From this, the following recommendations are proposed:

Application - WTR can provide useful amounts of major and secondary nutrients, and the project has identified possible ways forward for regularly applying WTR to agricultural and forestry land, and for one-off use on restoration sites. For WTR to be approved for application, benefit to ecology or agriculture must be demonstrated. However, ultimately, the rate and suitability of application of WTR is dictated by the properties of the receiving soil and requirements of the vegetation and the WTR application rate should be determined by annual soil tests.

In agriculture and forestry, WTR can be applied as a sole treatment (regulated under the waste management controls discussed above), and a separate application of non-waste fertiliser, e.g., manure or slurry may be made, if necessary (this avoids creating a material mixture of WTR and non-waste fertiliser which may subject the non-waste fertilisers to the management controls of waste). When applying WTR to restoration sites, a separate application of biosolids may be recommended to reduce risks of under-provision or inadvertent immobilisation of key nutrients, particularly phosphorus. WTR and biosolids may also be beneficial for restoration activities compared with using biosolids alone, as WTR typically provides more stable organic matter than biosolids. It is recommended that control of WTR land spreading, under exemptions, is maintained and that spreading follows the principles of General Binding Rule 18, particularly taking into account the season and prevention of pollution of waters by maintaining appropriate buffer strips. However, consideration should be given to exploring the possibility of getting an End-of-Waste status for WTR in the long-term.

Application rate – Annual WTR application rate to agricultural land of 50-150 t ha^{-1} has predominately been regarded as suitable in published literature. In England and Wales, application rates for agriculture are typically in the range of 20 – 60 t ha^{-1}. It appears that routine monitoring of soil properties and crop/tree growth is either not widely carried out at WTR spreading sites and/or data from such monitoring has not been widely reported, leading to limited knowledge of the long-term benefits/impacts of WTR use on both agricultural and forestry land. Further investigation into WTR application to land is required through test applications to understand changes to physical and chemical soil properties alongside monitoring of long-term effects of WTR spreading. With application to land becoming more prevalent, leading to a fuller understanding of the above, a more accurate range of application rates, that are likely to be suitable for Scotland, can be determined.

Circular economy - The project has identified benefits in relation to the principles of the Circular Economy through increasing the use of WTR to agricultural land. Benefits to the circular economy in Scotland are achieved by reducing distance travelled from SW Water Treatment Works to local application locations. Additional benefits are through the valorisation of the WTR where the beneficial nitrogen content of the WTR can displace the use of nitrogen-based fertiliser leading to a reduction of CO_2 emissions, in keeping with principles of circular economy and contributing to climate change mitigation. More information is required to develop a full lifecycle analysis to explore the most beneficial use of WTR within a circular economy. The life cycle analysis process will enable a detailed comparison to be made between different outlets for WTR alongside application to land, with a view to maximising circular economy benefits.

Circumstances when to use and not to use WTR - The project has identified circumstances in which to use and not to use WTR based on composition and receiving soil properties. Where there is a need for major and secondary nutrients, WTR can be used. WTR is useful to increase total nitrogen content in soil and may increase organic matter content. WTR is useful in providing high sorption capacity, especially for phosphorus, and for increasing soil cation exchange capacity. WTR is unsuitable for use with soils with pH <5.5 and in soils high in extractable sulphur (> 50 mg kg^{-1}, TN685 FAS). In Scotland, leaching of P is less likely than in other parts of the world, as Scottish soils tend to have lower pH and significant P fixation by Al occurs at pH values below 6. According to SRUC Technical Note TN714, 64% of arable and grassland soils in Scotland have a soil pH of 5.5-6.25, with 20.3% above and 16.1% below this range. Therefore, erosion and runoff are more likely mechanisms for P transport to streams and water bodies following WTR spreading in much of Scotland. Lateral flow transport of dissolved P through soil is also a risk if there is heavy rainfall soon after WTR application.

Pre-application analysis – Alongside acknowledged pH and nutrient content parameters, particle size distribution of both the receiving soil and WTR should be analysed to ensure particle size suitability for the chosen application. Some WTR tend to have a high percentage of fine particles so if flooding is a concern, it may not be appropriate to apply fine-grained WTR to land as this will reduce hydraulic conductivity of soil. If water retention is an issue, (i.e., the receiving soil is sandy) then application of a fine-grained WTR will result in an increase in water retention capacity which is likely to be beneficial.

5.1 Further research

Application of WTR to land should continue, with appropriate monitoring, whilst further desk and field work is undertaken to understand the full benefits and disbenefits of the application of WTR to soil properties in the Scottish context, for example:

- Scottish field trials to investigate WTR impact on plant growth and uptake of nutrients in plants.
- Develop a database of soils that can receive WTR, that is accessible to both SEPA and SW, building on site investigation and sample analysis.
- More monitoring of long-term effects of WTR spreading.
- Develop a full lifecycle analysis to explore the costs/benefits of land spreading WTR to achieve circular economy goals.
- Analyse WTR impact on Scottish soil physical and chemical properties.
- For site restoration, research to assess the impact of applications of WTR and WWTR on P availability. Assess public perception of WTR use on agricultural food production, land restoration, forestry, and ecological benefits.
- Further develop the Decision Support Tool (DST) to incorporate layers of existing soil data into an online system, to enable integration and improved access that makes use of platform independent Javascript or RShiny.
- Develop a data visualisation app which will automatically adapt to the device used. This will assist the integration of data and engage with real time agronomic data in the field.

6 References

ADAS (2001). The safe sludge matrix, 3rd Edition. http://adlib.everysite.co.uk/resources/000/094/727/SSMatrix.pdf

AFNOR (2015). FD X33-020 Drinking water treatment sludge - Good practices FD X33-020 National standards and national normative documents. https://www.boutique.afnor.org/en-gb/standard/fd-x33020/drinking-water-treatment-sludge-good-practices/fa177009/45775

AHDB (2020). Nutrient Management Guide (RB209) Section 2 Organic Materials. https://ahdb.org.uk/knowledge-library/rb209-section-2-organic-materials

Ahmed, M., Grant, C. D., Oades, J. M., Tarrant, P. (1998). Use of water treatment sludge. Australian Water and Wastewater Association, 25, 11–16.

Agyin-Birikorang, S., Oladeji, O.O., O'Connor, G.A., Obreza, T.A., Capece, J.C. (2009). Efficacy of drinking-water treatment residual in controlling off-site phosphorus losses: A field study in Florida. *Journal of Environmental Quality*, 38, 1076–1085. doi:10.2134/jeq2008.0383.

Babatunde, A.O., Zhao, Y.Q. (2007). Constructive approaches to water treatment works sludge management: an international review of beneficial reuses. Critical Reviews in *Environmental Science and Technology*, 37(2), 129-164.

Basta, N.T., Busalacchi, D.M., Hundal, L.S, Kumar, K. Dick, R.P., Lanno, R.P., Carlson, J., Cox, A.E., Granato, T.C (2016). Restoring ecosystem function in degraded urban soil using biosolids, biosolids blend, and compost. *Journal of Environmental Quality*, https://doi.org/10.2134/jeq2015.01.0009

Bayley, R.M., Ippolito, J.A., Stromberger, M.E., Barbarick, K.A., Paschke, M.W. (2008). Water treatment residuals and biosolids co-applications affect phosphatases in a semi-arid rangeland soil. *Communications in Soil Science and Plant Analysis*, 39(19-20), 2812-2826. DOI: 10.1080/00103620802432733

Blakemore, R., Chandler, R., Surrey, T., Ogilvie, D., Walmsley, N. (1998). Management of water treatment plant residuals in New Zealand, first ed. Water Supply Managers' Group, New Zealand Water and Wastes Association, Auckland, pp. 56.

Bugbee, G.T., Frink, C.R. (1985). Alum sludge as a soil amendment: effects on soil properties and plant growth. *Connecticut Agriculture Experimental Station Bulletin*, 827.

Busalacchi, D.M. (2012). Evaluation of biosolids as a soil amendment for use in ecological restoration. Master of Science, Ohio State University, Environmental Science Restoration. http://rave.ohiolink.edu/etdc/view?acc_num=osu1332429180

Caniani, D., Masi, S., Mancini, I.M., Trulli, E. (2013). Innovative reuse of drinking water sludge in geo-environmental applications. *Waste Management*, 33, 1461-1468.

Clarke, R., Peyton, D., Healy, M.G., Fenton, O., Cummins, E. (2016). A quantitative risk assessment for metals in surface water following the application of biosolids to grassland. *Science of the Total Environment*, 566, 102-112.

Code of Federal Regulations https://ecfr.federalregister.gov/current/title-40/chapter-I/subchapter-I/part-257/subpart-A/section-257.1 (accessed on Feb. 9, 2022).

Crooks, B., Sinclair, A., Edwards, T. (2019). Technical note TN714. Liming materials and recommendations. https://www.fas.scot/downloads/tn714-liming-materials-and-recommendations/.

Cundill, A.P. (2021) Personal Communication.

Cundill, A.P., Erber, C., Dobbie, K.E., Shepherd, J.A. (2012). Application of organic waste to land in Scotland – Benefits, risks and reality? SEPA, Erskine Court, Stirling, FK9 4TR3.

Dahlgaard, J.J., Dahlgaard-Park, S.M. (2006). Lean production, six sigma quality, TQM and company culture. The TQM magazine.

Dassanayake, K.B., Jayasinghe, G.Y., Surapaneni, A., Hetherington, C. (2015). A review on alum sludge reuse with special reference to agricultural applications and future challenges. *Waste Management*, 38, 321-335.

Dayton, E.A., Basta, N.T. (2001). Characterization of drinking water treatment residuals for use as a soil substitute. *Water Environment Research*, 73, 52-57.

Dayton, E.A., Basta, N.T., Jakober, C.A., Hattey, J.A. (2003). Using Treatment Residuals to reduce phosphorous in agricultural runoff. American Water Works Association, 95(4), 151-158.

Earthcare (2020). The benefits and challenges associated with application of water treatment residuals (WTR) to UK agricultural land. Prepared by Litterick, A., Wood, M., Sinclair, A.

Elliott, H.A., Dempsey, B.A.,Hamilton, D.W., Dewolfe, J.R. (1990). Land application of water treatment sludges: impact and management. Final report. Denver CO, AWWA Research Foundation.

Elliott, H.A., Dempsey, B.A. (1991). Agronomic effects of land application of water treatment sludge. *Journal of the American Water Works Association*, 83, 126-131.

EPA Comprehensive Environmental Response, Compensation, and Liability Act https://www.epa.gov/laws-regulations/summary-comprehensive-environmental-response-compensation-and-liability-act (accessed on 9th Feb., 2022).

EPA Clean Air Act https://www.epa.gov/laws-regulations/summary-clean-air-act (accessed on 9th Feb. 2022).

EPA Clean Water Act https://www.epa.gov/laws-regulations/summary-clean-water-act Version 2 February 2013 (accessed on 7th July 2021).

EPA Resource Conservation and Recovery Act (RCRA) Laws and Regulations https://www.epa.gov/rcra (accessed on 9th Feb. 2022).

European Commission. Groundwater in the Water Framework Directive. https://ec.europa.eu/environment/water/water-framework/groundwater/framework.htm (accessed 9th Feb. 2022).

European Commission, 2018/246. Report from the Commission to the Council and the European Parliament on the implementation of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources based on Member State reports for the period 2012–2015 https://www.actu-environnement.com/media/pdf/news-31230-rapport-pollution-nitrates-commission-europeenne.pdf (accessed 9th Feb. 2022).

European Commission, Groundwater as a resource (accessed 9th Feb. 2022). https://ec.europa.eu/environment/water/water-framework/groundwater/resource.htm

Farm Advisory Service (2017). Technical note TN685. Sulphur Recommendations for Crops. https://www.fas.scot/downloads/tn685-sulphur-recommendations/ (accessed 9th Feb. 2022).

Farm Advisory Service (2019). TN609 Agricultural use of biosolids, composts, anaerobic digestates and other industrial organic fertilisers.

Farm Advisory Service (2020). FAS/SRUC technical note TN715. Phosphate and potash recommendations for crops grown in Highland and Islands 10pp.

Farm Advisory Service (2021). Cross compliance checklists, FAS https://www.fas.scot/publication/cross-compliance-checklists/

FDEP (2021). Biosolids Monitoring, Record Keeping, Reporting, and Notification. Florida Administrative Code (2021). Chapter 62-640 Biosolids. https://www.flrules.org/gateway/ChapterHome.asp?Chapter=62-640 (accessed 9th Feb. 2022).

FLS, Forestry and Land Scotland (2021). Key principles for the remediation of former opencast coal sites for woodland establishment V7.2.

Frosch, R.A., Gallopoulos, N.E. (1989). Strategies for manufacturing. *Scientific American*, 261(3), 144-153.

Gallimore, L.E., Basta, N.T., Storm, D.E., Storm, D.E., Payton, M.E., Huhnke, R.H., Smolen, M.D. (1999). Water treatment residual to reduce nutrients in surface runoff from agricultural land. *Journal of Environmental Quality*, 28, 1474-1478.

Geertsema, W.S., Knocke, W.R., Novak, J.T., Dove, D. (1994). Long-term effects of sludge application to land. American Water Works Association, 86, 64–74.

Godfrey, L., Oelofse S. (2017). Historical Review of Waste Management and Recycling in South Africa. *Resources*, 6, 57.

Haynes, R.J., Zhou, Y.F. (2015). Use of alum water treatment sludge to stabilize C and immobilize P and metals in composts. *Environmental Science and Pollution Research*, 22(18), 13903-13914. DI 10.1007/s11356-015-4517-4.

Helserman, J. E. (2013). Technical Support Document to the Development of: Guidelines for the Utilisation and Disposal of Water Treatment Residues. Water Research Commission, Report No. 1723/1/13.

Howells, A.P., Lewis, S.J., Beard, D.B., Oliver, I.W. (2018). Water treatment residuals as soil amendments: Examining element extractability, soil porewater concentrations and effects on earthworm behaviour and survival. *Ecotoxicology and Environmental Safety*, 162, 334–340. https://doi.org/10.1016/j.ecoenv.2018.06.087 (accessed 9th Feb. 2022).

House of Commons, HC 656 (2018). Environmental Audit Committee. UK Progress on Reducing Nitrate Pollution.

Ibrahim, M.M., Mahmoud, E.K., Ibrahim, D.A. (2015). Effects of vermicompost and water treatment residuals on soil physical properties and wheat yield. *International Agrophysics*, 29, 157-164. doi: 10.1515/intag-2015-0029.

Ippolito, J.A., Barbarick K.A., Redente, E.F. (2002). Combinations of water treatment residuals and biosolids affect two range grasses. *Communications in Soil Science and Plant Analysis*, 33(5-6), 831-844. DOI: 10.1081/CSS-120003069 (accessed 9th Feb. 2022).

Ippolito, J.A., Barbarick, K.A., Elliott, H.A. (2011). Drinking water treatment residuals: a review of recent uses. J*ournal of Environmental Quality*, 40(1), 1-12. https://eprints.nwisrl.ars.usda.gov/1407/1/1377.pdf (accessed 9th Feb. 2022).

Ippolito, J.A., Scheckel, K.G., Barbarick, K.A. (2009). Selenium adsorption to aluminium-based water treatment residuals. *Journal of Colloid Interface Science*, 338, 48–55.

International Standards Organisation (2021). Soil, treated biowaste and sludge – determination of pH. ISO 10390:2021 https://www.iso.org/standard/75243.html (accessed 9th Feb. 2022).

International Standards Organisation (1995) Soil quality — Determination of total nitrogen — Modified Kjeldahl method. ISO 11261:1995. https://www.iso.org/standard/19239.html (accessed 9th Feb. 2022).

Judy, J., Silveira, M., Agyin-Birikorang, S., O'Connor G. (2019). Are alum-based drinking water treatment residuals safe for land application? SL 299. Department of Soil and Water Sciences, UF/IFAS Extension. Original publication date July 2009. Revised June 2019.

Keeley, J., Jarvis, P., Judd, S.J. (2014). Coagulant recovery from water treatment residuals: a review of applicable technologies. *Critical Reviews in Environmental Science and Technology*, 44(24), 2675-2719.

Kirchherr, J., Reike, D., Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221-232.

Korhonen, J., Honkasalo, A., Seppälä, J. (2018). Circular economy: the concept and its limitations. *Ecological Economics*, 143, 37-46.

Lin, S.D., Green, C.D. (1987). Wastes from water treatment plants: Literature review results of an Illinois survey and effects of alum sludge application to cropland. Illinois State Water Survey Water Quality Section.

Lombi, E., Stevens, D.P., McLaughlin, M.J. (2010). Effect of water treatment residuals on soil phosphorus, copper and aluminium availability and toxicity. *Environmental Pollution*, 158(6), 2110-2116. DI 10.1016/j.envpol.2010.03.006.

Madison, R.K., McDowell, L.R., O'Connor, G.A., Wilkinson, N.S., David, P.A., Adesogan, A.T., Felix, T.L, Brennan, M. (2009). Effects of aluminum from water-treatment-residual applications to pastures on mineral status of grazing cattle and mineral concentrations of forages. *Communications in Soil Science and Plant Analysis*, 40(19-20), 3077-3103. https://doi.org/10.1080/00103620903261635.

Makris, K.C., Harris, W.G., O'Connor, G.A., Obreza, T.A. (2004). Phosphorus immobilization in micropores of drinking-water treatment residuals: implications for long-term stability. *Environmental Science & Technology*, 38(24), 6590-6596. https://pubs.acs.org/doi/10.1021/es049161j (accessed 9th Feb. 2022).

Mahdy, A.M., Elkhatib, E.A., Fathi, N.O., Lin, Z.-Q. (2009). Effects of co-application of biosolids and water treatment residuals on corn growth and bioavailable phosphorus and aluminum in alkaline soils in Egypt. *Journal of Environmental Quality*, 38(4), 1501-1510. https://doi.org/10.2134/jeq2008.0335 (accessed 9th Feb. 2022).

Mahmoud, E.K., Ibrahim M.M. (2012). Effect of vermicompost and its mixtures with water treatment residuals on soil chemical properties and barley growth. *Journal of Soil Science and Plant Nutrition*, 12(3), 431-440. http://dx.doi.org/10.4067/S0718-95162012005000005 (accessed 9th Feb. 2022).

Mbavarira, T.M., Grimm, C., (2021). A systemic view on circular economy in the water industry: learnings from a Belgian and Dutch case. *Sustainability*, 13(6), 3313.

Millennium Ecosystem Assessment (2005). Ecosystems and human well-being: Synthesis. Island Press, Washington, DC.

Mokonyama, S., Schalkwyk, M., Rajagopaul, R. (2017). Guidelines and good practices for water treatment residues handling, disposal and reuse in south Africa. Report to the Water Research Commission, WRC Report No. TT 738/17. http://www.wrc.org.za/wp-content/uploads/mdocs/TT738.pdf (accessed 9th Feb. 2022).

Moran, S. (2018). Chapter 4 - Engineering science of water treatment unit operations. Editor(s): Seán Moran, An Applied Guide to Water and Effluent Treatment Plant Design, Butterworth-Heinemann. 39-51, ISBN 9780128113097. https://doi.org/10.1016/B978-0-12-811309-7.00004-7 (accessed 9th Feb. 2022).

Mraz, A.L., Tumwebaze, I.K., McLoughlin, S.R., McCarthy, M.E., Verbyla, M.E., Hofstra, N., Rose, J.B., Murphy, H.M. (2021). Why pathogens matter for meeting the united nations' sustainable development goal 6 on safely managed water and sanitation. *Water Research*, 189, 116591.

Musacchio, A., Re, V., Mas-Pla, J. et al. (2020). EU Nitrates Directive, from theory to practice: Environmental effectiveness and influence of regional governance on its performance. *Ambio*, 49, 504–516. https://doi.org/10.1007/s13280-019-01197-8 (accessed 9th Feb. 2022).

Nair, V.D. (2014). Soil phosphorus saturation ratio for risk assessment in land use systems. *Frontiers in Environmental Science – Agroecology*. https://doi.org/10.3389/fenvs.2014.00006

Novak, J.T., Knocke, W.R., Geertsema, W., Dove, D., Taylor, A., Mutter, R. (1995). Long-term impacts on water quality and forest soils. In: An Assessment of Cropland Application of Water Treatment Residuals. Am. Water Works Assoc. Res. Found., Am. Water Works Assoc., Denver, Colo.

Novak, J.M., Watts, D.W. (2004). Increasing the phosphorus sorption capacity of South Eastern Coastal Plain soils using water treatment residuals. *Soil Science*, 169, 206-214.

Novak, J., Szogi, A.A., Watts, D.W., Busscher, W. (2007). Water treatment residuals amended soils release Mn, Na, S, and C. *Soil Science*, 172. 10.1097/ss.0b013e3181586b9a.

New Zealand Water and Wastes Association NZWWA. (1998). Handbook of Management of Water Treatment Plant Residuals in New Zealand (ISBN 1-877134). New Zealand Water and Waste Association. https://www.waternz.org.nz/Attachment?Action=Download&Attachment_id=218 (accessed 9th Feb. 2022).

Oladeji, O.O., O'Connor, G.A., Sartain, J.B., Nair, V.D. (2007). Controlled application rate of water treatment residual for agronomic and environmental benefits. *Journal of Environmental Quality*, 36(6), 1715-1724.

Ozdemir, O.D., Piskin, S. (2012). Characterization and environment risk assessment of galvanic sludge. *Journal of the Chemical Society of Pakistan*, 34(4), 1032-1036.

Planet Nutrient Management. http://www.planet4farmers.co.uk/ (accessed 9th Feb. 2022).

Puntillo, P., Gulluscio, C., Huisingh, D., Veltri, S. (2021). Re-evaluating waste as a resource under a circular economy approach from a system perspective: Findings from a case study. *Business Strategy and the Environment*, 30(2), 968-984.

Queensland Government (2019). End of Waste Code (EOW). https://environment.des.qld.gov.au/__data/assets/pdf_file/0035/89963/wr-eowc-approved-water-treatment-residuals.pdf (accessed 9th Feb. 2022).

Queensland Government (2019). End of waste (EOW) framework, https://environment.des.qld.gov.au/management/waste/business/end-of-waste-classification#end_of_waste_codes (accessed 9th Feb. 2022).

Ren, B., Zhao, Y., Ji, B., Wei, T., Shen, C. (2020). Granulation of Drinking Water Treatment Residues: Recent Advances and Prospects. *Water*, 12, 1400; doi:10.3390/w12051400.

Republic of South Africa. National Environmental Management: Waste Amendment Act 26 of 2014. Government Gazette No. 36784, Notice No. 449. 2014. Available online: https://www.environment.gov.za/sites/default/files/legislations/nemwa_actno26of2014.pdf (accessed 9th Feb. 2022).

Robert, J.G., Edward, C.K. (1987). Silvicultural application of alum sludge. *Journal of American Water Works Association*, 79(6), 84–88.

Samie, A., Ntekele, P. (2014). Genotypic detection and evaluation of the removal efficiency of *Giardia duodenalis* at municipal wastewater treatment plants in Northern South Africa. *Tropical Biomedicine*, 31(1), 122-33.

Scottish Environment LINK (2020a). *A Circular Scotland: briefing*. Available paper at: https://www.scotlink.org/wp-content/uploads/2020/11/A-circular-Scotland-final-nov-2020.pdf (accessed 9th Feb. 2022).

Scottish Environment Protection Agency (SEPA), Accessed 30/05/21. Waste Guidance. https://www.sepa.org.uk/regulations/waste/guidance/ (accessed 9th Feb. 2022).

Scottish Environment Protection Agency (SEPA) (2019). The Water Environment (Controlled Activities) (Scotland) Regulations 2011 (as amended). A Practical Guide. Version 8.4. https://www.sepa.org.uk/media/34761/car_a_practical_guide.pdf (accessed 9th Feb. 2022).

Scottish Environment Protection Agency (2015). Technical Guidance Note for Paragraph 7 exemptions https://www.sepa.org.uk/media/105235/the-treatment-of-land-for-agricultural-benefit-or-ecological-improvement-technical-guidance-note-for-paragraph-7-exemptions.pdf (accessed 9th Feb. 2022).

Scottish Environment Protection Agency (2015) Technical Guidance Note for Paragraph 9 exemptions https://www.sepa.org.uk/media/105209/the-reclamation-or-improvement-of-land-technical-guidance-note-for-paragraph-9-exemptions.pdf (accessed 9th Feb. 2022).

Scottish Environment LINK (2020b). Topical Survey. Avaliable at: https://www.scotlink.org/wp-content/uploads/2020/05/CE-survey-report-May-2020.pdf (accessed 9th Feb. 2022).

Scottish Executive (2005). Prevention of Environmental Pollution from Agricultural Activity (PEPFAA) Code. Scottish Executive, Edinburgh. https://www.gov.scot/publications/prevention-environmental-pollution-agricultural-activity-guidance/ (accessed 9th Feb. 2022).

Scottish Government (2002). Water Industry (Scotland) Act 2002. https://www.legislation.gov.uk/asp/2002/3/contents (accessed 9th Feb. 2022).

Scottish Government (2005). Water Services etc. (Scotland) Act 2005, Section 22. https://www.legislation.gov.uk/asp/2005/3/section/22 (accessed 9th Feb. 2022).

Scottish Government (2010). Zero Waste Plan. https://www.gov.scot/publications/scotlands-zero-waste-plan/ (accessed 9th Feb. 2022).

Scottish Government (2011a). The Waste Management Licensing (Scotland) Regulations 2011. https://www.legislation.gov.uk/ssi/2011/228/contents/made (accessed 9th Feb. 2022).

Scottish Government (2011b). Water Environment (Controlled Activities) (Scotland) Amendment (CAR) Regulations 2013 (Amended); https://www.legislation.gov.uk/ssi/2011/209/contents/made (accessed 9th Feb. 2022).

Scottish Government (2015). Maps of the five Nitrate Vulnerable Zones (NVZs) in Scotland (accessed 9th Feb. 2022). https://www.gov.scot/publications/nitrate-vulnerable-zones-maps

Scottish Government (2016). Nitrate vulnerable zones: guidance for farmers. https://www.gov.scot/publications/nitrate-vulnerable-zones-guidance-for-farmers/ (accessed Feb. 9, 2022).

Scottish Government (2016). *Making Things Last – A Circular Economy Strategy for Scotland*. https://www.gov.scot/publications/making-things-last-circular-economy-strategy-scotland/pages/17/ (accessed 9th Feb. 2022).

Scottish Government (2018). Climate Change Plan. https://www.gov.scot/publications/scottish-governments-climate-change-plan-third-report-proposals-policies-2018/pages/15/ (accessed 9th Feb. 2022).

Scottish Government (2019). Developing Scotland's Circular Economy – Proposals for Legislation. https://www.gov.scot/publications/delivering-scotlands-circular-economy-proposals-legislation/pages/3/ (accessed 9th Feb. 2022).

Scottish Government (2019). Circular Economy strategy and bill proposals (2019). https://www.gov.scot/news/circular-economy-bill/ (accessed 9th Feb. 2022).

Scottish Government (2019). Scotland's 2045 net-zero emission target. https://www.gov.scot/news/reaching-net-zero/ (accessed 9th Feb. 2022).

Scottish Government (2019). Protecting Scotland's Future: The Government's Programme for Scotland 2019-2020 (www.gov.scot).

Scottish Government (2020). Scotland's Programme for Government 20-21. https://www.gov.scot/publications/protecting-scotland-renewing-scotland-governments-programme-scotland-2020-2021/ (accessed 9th Feb. 2022).

Scottish Government. Agriculture and the environment. https://www.gov.scot/policies/agriculture-and-the-environment/nvz/ (accessed 9th Feb. 2022).

Scottish Statutory Instruments (2003). Water Environment and Water Services (Scotland) Act 2003. https://www.legislation.gov.uk/asp/2003/3/part/1/2015-09-14 (accessed 9th Feb. 2022).

Scottish Statutory Instruments (SSI) 2008/298 (2008). The Action Programme for Nitrate Vulnerable Zones (Scotland) Regulations. https://www.legislation.gov.uk/ssi/2008/298/pdfs/ssi_20080298_en.pdf (accessed 9th Feb. 2022).

Scottish Statutory Instruments (SSI) 2008/298; Schedule 3, (2008). https://www.legislation.gov.uk/ssi/2008/298/schedule/3/made (accessed 9th Feb. 2022).

Scottish Statutory Instruments (SSI) 2008/298; Regulation 24, (2008). https://www.legislation.gov.uk/ssi/2008/298/regulation/24/made (accessed 9th Feb. 2022).

Scottish Statutory Instruments (2009). The Water Environment (Groundwater and Priority Substances) (Scotland) Regulations 2009. The Water Environment (Groundwater and Priority Substances) (Scotland) Regulations 2009 (legislation.gov.uk) (accessed 9th Feb. 2022).

Scottish Statutory Instruments (2011). Waste Management Licensing (Scotland) Regulations 2011 (exemptions – paragraph 9, 7). https://www.legislation.gov.uk/sdsi/2011/9780111012147/contents (accessed 9th Feb. 2022).

Scottish Statutory Instruments (2012). The Pollution Prevention and Control (Scotland) Regulations 2012 SSI 2012/360. https://www.legislation.gov.uk/ssi/2012/360/contents/made (accessed 9th Feb. 2022).

Scottish Statutory Instruments (2013). Water Environment (Controlled Activities) (Scotland) Amendment (CAR) Regulations 2013 (as Amended). https://www.legislation.gov.uk/ssi/2021/412/introduction/made (accessed 9th Feb. 2022).

Scottish Statutory Instruments (2013). Water Environment (Controlled Activities) (Scotland) Amendment (CAR) Regulations 2013 (as Amended). https://www.legislation.gov.uk/ssi/2013/176/pdfs/ssi_20130176_en.pdf (accessed 9th Feb. 2022).

Scottish Statutory Instruments (SSI) (2017). The Water Environment (Miscellaneous) (Scotland) Regulations, 2017. https://www.legislation.gov.uk/ssi/2017/389/pdfs/ssi_20170389_en.pdf (accessed 9th Feb. 2022).

Scottish Water (2020). The Scottish Water (Objectives: 2021 to 2027) Directions (2020). https://www.gov.scot/publications/scottish-water-directions-2020/ (accessed 9th Feb. 2022).

Scottish Water (2020). Management of Biosolids Recycling, Water Industry Journal. https://www.waterindustryjournal.co.uk/management-of-biosolids-recycling-2 (accessed 9th Feb. 2022).

Scottish Water (2021). Scottish Water Bioresource Strategy. https://www.scottishwater.co.uk/Help-and-Resources/Document-Hub/Key-Publications/Strategic-Plan (accessed 9th Feb. 2022).

Scottish Water (2021). Net Zero Carbon Emission Targets for Scottish Water 2040. https://www.scottishwater.co.uk/Help-and-Resources/Document-Hub/Key-Publications/Net-Zero-Emissions (accessed 9th Feb. 2022).

Scottish Water (2021). Water Industry Vision. https://www.scottishwater.co.uk/about-us/what-we-do/the-water-industry-in-scotland (accessed 9th Feb. 2022).

South Australia (1993). Environment Protection Act 1993 (SA). https://www.legislation.sa.gov.au/LZ/C/A/ENVIRONMENT%20PROTECTION%20ACT%201993/CURRENT/1993.76.AUTH.PDF (accessed 9th Feb. 2022).

South Australia (1993). Environnent Protection Act 1993 (SA) Section 25. http://classic.austlii.edu.au/au/legis/sa/consol_act/epa1993284/s25.html (accessed 9th Feb. 2022).

SRUC (2016). Valuing Your Soils: Practical guidance for Scottish farmers. https://www.sruc.ac.uk/media/4qgfjtuh/valuing-your-soils.pdf (accessed 9th Feb. 2022).

Smart Water Fund (2015). Alum Sludge Reuse Final report. https://waterportal.com.au/swf/projects/item/12-investigation-of-alum-recycling-and-reuse (accessed 9th Feb. 2022).

Sydney Water (2021). Annual Environmental Performance Report 2019 – 20, Sydney Water SW147 02/21.

Sydney Water Annual Report (2011). Environmental Indicators https://www.parliament.nsw.gov.au/tp/files/41602/4.%20Sustainability_indicators.pdf

Sheppard, L.J., Floate, M.J.S. (1984). The effects of soluble-Al on root growth and radicle elongation. *Plant and Soil*, 80(2), 301-306.

Silveira, M.L., Driscoll, J.L., Silveira, C.P., Graetz, D.A., Sollenberger, L.E., Vendramini, J. (2013). Land application of aluminum water treatment residual to Bahiagrass pastures: soil and forage responses. *Agronomy Journal*, 105, 796–802.

Sun, Q., Aguila, B., Song, Y., Ma, S. (2020). Tailored porous organic polymers for task-specific water purification. *Accounts of Chemical Research*, 53(4), 812-821. DOI: 10.1021/acs.accounts.0c00007. https://dx.doi.org/10.1021/acs.accounts.0c00007?ref=pdf (accessed 9th Feb. 2022).

Sutherland J. (2019). Soil analysis in the West Highlands and Islands. Technical note TN710. https://www.fas.scot/downloads/tn710-soil-analysis-in-the-west-highlands-and-islands/ (accessed 9th Feb. 2022).

Tay, D.Y.Y., Fujinuma, R., Wendling, L.A. (2017). Drinking water treatment residual use in urban soils: Balancing metal immobilization and phosphorus availability. *Geoderma*, 305, 113-121.

Teagasc (2021). Major and micro nutrient advice for productive agricultural Crops. 5th Edition. Teagasc - The Agriculture and Food Development Authority, Wexford, UK.

TEEB (2010). The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A synthesis. *TEEB*. Pavan Sukhdev et al.

Turner, T., Wheeler, R., Stone, A., Oliver, I. (2019). Potential alternative reuse pathways for water treatment residuals: Remaining barriers and questions—A review. *Water Air and Soil Pollution*, 230, 227. https://doi.org/10.1007/s11270-019-4272-0 (accessed 9th Feb. 2022).

UK Government (2016). No. 1190. The Nitrate Pollution Prevention (Amendment) Regulations 2016. https://www.legislation.gov.uk/uksi/2016/1190/contents/made (accessed 9th Feb. 2022).

UK Government. EU legislation and UK law (accessed 9th Feb. 2022). https://www.legislation.gov.uk/eu-legislation-and-uk-law

UK Government (1995). The Environment Act 1995 (accessed 9th Feb. 2022). https://www.legislation.gov.uk/ukpga/1995/25/contents

UK Government (2021). Guidance: Cross compliance 2021 Gov.uk (accessed 9th Feb. 2022). https://www.gov.uk/guidance/cross-compliance-2021

UK Progress on Reducing Nitrate Pollution; 22 November 2018 (accessed 9th Feb. 2022). https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/656/65602.htm

Ulmert, H.A.N.S., Sarner, E. (2005). The ReAl Process-a combined membrane and precipitation process for recovery of aluminium from waterwork sludge. *Vatten*, 61(4), p.273.

UN Food and Agriculture Organization, (2005). Agricultural use of sewage sludge. UN Food and Agriculture Organization. http://www.fao.org/3/T0551E/t0551e08.htm

Vasilyev, O., Vasilyev, A., Eliseev, I., Schiptsova, N., Lozhkin, A., Fadeeva, N. (2020). Change of the chemical composition of potato plants when applying organic fertilizers under the conditions of the Chuvash Republic. In: (eds) Mardaryev, A., Godmchuk, A., Karakchieva, N., proceedings of the International Agroscience Conference (Agroscience-2020), Cheboksary, Russia, April 2020. IOP Conference Series-Earth and Environmental Science 604, AR 012012. DI 10.1088/1755-1315/604/1/012012.

Verlicchi, P., Masotti, L. (2000). Reuse of drinking water treatment plants sludges in agriculture: problems, prospectives and limitations. Proceedings of the 9th International Conference on the FAO ESCORENA Network on recycling of agricultural, municipal and industrial residues in agriculture, Gargano, Italy, 6-9 September 2000.

Wang, M.-B., Hu, Q.-C. (2013). Root characteristics of winter wheat as affected by co-application of biosolids and water treatment residuals. https://en.cnki.com.cn/Article_en/CJFDTotal-SXDR200702032.htm (accessed 9th Feb. 2022).

WaterWorld (2021). Biosolids: Never ending problem or increasing opportunity? | WaterWorld (accessed 9th Feb. 2022).

Western Association of Agricultural Experiment Station Directors (WAAESD) (2019).Beneficial use of residuals to improve soil health and protect public, and ecosystem health. https://www.nimss.org/projects/view/mrp/outline/18624 (accessed 9th Feb. 2022).

Yang, Y., Tomlinson, D., Kennedy, S., Zhao, Y.Q. (2006). Dewatered alum sludge: a potential adsorbent for phosphorus removal. *Water Science and Technology*, 54 (5), 207–213.

Zhao, Y.Q., Babatunde, A.O., Hu, Y.S., Kumar, J.L.G., Zhao, X.H. (2011). Pilot field-scale demonstration of a novel alum sludge-based constructed wetland system for enhanced wastewater treatment. *Process Biochemistry*, 46 (1), 278–283.

Zhao, Y.Q. (2002). Enhancement of alum sludge dewatering capacity by using gypsum as skeleton builder. *Journal of Colloids and Surfactants*, 211, 205–212.

Zhao, Y., Liu, R., Awe, O.W., Yang, Y., Shen, C. (2018). Acceptability of land application of alum-based water treatment residuals – An explicit and comprehensive review. *Chemical Engineering Journal*, 353, 717-726. https://doi.org/10.1016/j.cej.2018.07.143 (accessed 9th Feb. 2022).

7 Appendices

Appendix 1. General Binding Rule 18

Table A1. Summarised General Binding Rule 18 (Scottish Statutory Instrument, 2017) for the storage and application of fertiliser (including wastes and waste-derived materials).	
GBR18. (a) The storage of fertiliser unless the storage is regulated by— (i) a waste management licence in terms of section 35 (waste management licence: general) of the Environmental Protection Act 1990(a); (ii) the Control of Pollution (Silage, Slurry and Agricultural Fuel Oil) (Scotland) Regulations 2003(a);	**(a)** No fertiliser may be **stored**, including temporarily in a mobile tank or bowser, on land that: (i) is within 10 metres of any— (1) river, burn, ditch or loch, as measured from the top of the bank; (2) wetland; or (3) transitional water or coastal water, as measured from the shoreline; (ii) is within 50 metres of any— (1) spring that supplies water for human consumption; or (2) well or borehole that is not capped in such a way so as to prevent the ingress of water;
	(iii) is waterlogged; (iv) has an average soil depth of less than 40 centimetres and overlies gravel or fissured rock, unless the fertiliser is stored in an impermeable container; or (v) is sloping (unless the fertiliser is inorganic or it is ensured that any run-off of fertiliser is intercepted (by means of a sufficient buffer zone or otherwise) to prevent it from entering any river, burn, ditch, wetland, loch, transitional water or coastal water towards which the land slopes); unless the fertiliser is stored in a building which is constructed and maintained to such a standard as is necessary to prevent run-off or seepage of fertiliser from the building;
(b) the application of any fertiliser.	**(g)** no organic fertiliser may be **applied** to land that— (i) is within 10 metres of any— (1) river, burn, ditch or loch, as measured from the top of the bank; (2) wetland; (3) transitional water or coastal water, as measured from the shoreline; or (4) opening into a surface water drainage system;
	(ii) is within 50 metres of any— (1) spring that supplies water for human consumption; or (2) well or borehole that is not capped in such a way so as to prevent the ingress of water; (iii) has an average soil depth of less than 40 centimetres and overlies gravel or fissured rock, except where the application is for forestry operations; (iv) is frozen (except where the fertiliser is farmyard manure), waterlogged, or covered with snow; or (v) is sloping, unless it is ensured that any run-off of fertiliser is intercepted (by means of a sufficient buffer zone or otherwise) to prevent it from entering any river, burn, ditch, wetland, loch, transitional water or coastal water towards which the land slopes;
	(**i**) fertilisers must not be applied to land: (i) in such amounts that the crop requirement for nitrogen is exceeded; (ii) in excess of the amount required to maintain the soil phosphorus status at acceptable agronomic levels; or
	(iii) during heavy rainfall or where heavy rainfall is forecast within 24 hours;
	(**l**) any equipment used to apply fertiliser must be maintained in a good state of repair; and
	(**m**) fertiliser must be applied on land in such a way and at such times that the risk of pollution of the water environment is minimised.

Appendix 2. Impacts and consequences on circular economy in Scotland

The circular economy is a concept that is currently being promoted throughout the European Union and by several other national governments including the United Kingdom, China, Japan and Canada, as well as several major businesses around the world (Korhonen et al., 2018).

It has become clear that the traditional linear extract-produce-use-dump material and energy flow model is an unsustainable approach (Frosch & Gallopoulos, 1989). The circular economy model provides an alternative flow model, one which is cyclical rather than linear. Unlike traditional recycling, the circular economy approach emphasises product, component and material reuse, refurbishment, repair, cascading and upgrading as well as solar, wind, biomass and other waste derived energy utilisation throughout the product life cycle (Korhonen et al., 2018). Whilst there is some understanding of how circular economy approaches generally work, there is no commonly accepted definition of circular economy (Kirchherr et al., 2017) and the practise has been predominantly developed and led by practitioners such as policy-makers, businesses, business consultants and business foundations and the topic has, to date, been relatively unexplored by scientific research (Korhonen et al., 2018).

In the linear approach to waste management, waste becomes a burden when trying to achieve operational efficiency in many businesses, which is why so many businesses implement strategies to minimise waste (Dahlgaard & Dahlgaard-Park, 2006). For businesses following a circular economy approach, an additional approach to minimising waste is adopted by viewing redundant or waste materials as a resource which can be reused, recycled, repaired or refurbished. This transformation of waste materials is one key aspect of the circular economy model and can be viewed as a continuum going from the vision of waste as a burden to the vision of waste as a potentially useful resource (Puntillo et al., 2021).

Circular economy guidance and legislation in Scotland

The Scottish Government developed and published a strategy in 2016 to help progress towards a more circular economy (Scottish Government, 2016). The strategy targeted four main priority areas where significant progress towards a circular economy could be made (Scottish Government, 2016):

- Food and drink, and the broader bioeconomy.
- Remanufacture.
- Construction and the built environment.
- Energy infrastructure.

The development of this strategy preceded proposed legislation which was brought forward in November 2019 as a Circular Economy Bill. Scottish Environment LINK (2020a) published a briefing paper which asks the Scottish Government to prioritise a Circular Economy Bill in the next parliamentary term (from May 2021; Scottish Environment LINK, 2020). Survey results from Scottish Environment LINK indicate that the transition to a more circular economy is popular amongst the public (Scottish Environment LINK, 2020b).

Within the proposals for legislation, the Scottish Government set out some key objectives which can be summarised as the following (Scottish Government, 2019):

- Reducing waste.
- Reducing litter.
- Reducing carbon and resource footprint.
- Increasing recycling rates and quality of recyclate.
- Maximising economic opportunities.

The proposals link directly to the United Nations Sustainable Development Goal 12: Ensure sustainable consumption and production patterns (United Nations, 2020). Sustainable growth is a key priority for the Scottish Government and the circular economy contributes heavily to the economic and environmental outcomes under the National Performance Framework where progress is measured through the carbon footprint and waste generator indicators. The proposals for legislation also set out a list of key targets (Scottish Government, 2019). The targets related to the reuse of WTR are as follows:

- Waste prevention.
    - o Reduce waste arising by 15% against the 2011 baseline by 2025.
- Landfill.
    - o No more than 5% of all waste going to landfill by 2025.
    - o No biodegradable municipal waste going to landfill by 2025.

There is a clear financial benefit to be derived from the recycling of WTR as opposed to sending them to landfill, which is becoming increasingly costly. In the UK, the landfill disposal cost for inert material rose to approximately £90 t^{-1} in 2018 from approximately £8 t^{-1} in 1996 (Turner et al., 2019).

The circular economy concept as applied to WTR can also be demonstrated through the recovery of valuable chemical resources, although investment and appropriate enabling legislation for this are both missing (Mbavarira & Grimm, 2021). The range of reuse options is shown in Table A2 Alternative uses for WTR as identified by Turner et al (2019).

Table A2. Alternative uses for WTR (from Turner et al 2019. Alternative Reuse Pathways for Water Treatment Residuals: Remaining Barriers and Questions).				
Potential market for end use			**Advantages**	**Disadvantages**
Sorption	Water remediation	Elemental contaminants	• Sorbs high amounts of individual or multiple contaminants • WTR have even greater sorption capacities	• Possible excessive P sorption • Leaching of some elements and compounds are still a concern
		Textile dye	• Very high removal rates	• Not economical currently • Disposal of produced product • Does not work for hydrophilic dyes
		Organic contaminants	• Possible remediation method for emerging contaminants • Could reduce chance of eutrophication	• Lack of research
	Constructed wetlands		• High removal efficiencies • Proven success in incorporating bio-sorption reactors and microbial fuel cells	• Clogging • Low demand for WTR
	Lakes and reservoirs		• Could reduce chance of eutrophication through nutrient control	• Leaching of some elements still under question
	Soil remediation		• Can sorb high amounts of organic and inorganic pollutants • Reduction of P runoff could reduce eutrophication	• Potentially excessive P sorption • May require co-application to negate crop yield reduction in certain circumstances • Potential impacts relating to leaching of Al and Fe from coagulants
Bulk land application			• Increases aeration • Provides sufficient N for plant growth • Can increase plant yield • Increased hydraulic conductivity	• Excessive P sorption • Co-application of P source may be required • Worries regarding the leaching of metals
Incorporation into construction materials	Bricks		• Could offer a disposal route for a large quantity of WTR • Can reduce production costs • Up to 15–20% WTR content will pass most brick product standards	• Higher sintering temperature may be required • Some leachates of concern • Reduction in strength above 15% WTR content
	Concrete and cement		• Can reduce production costs • Could offer a disposal route for a large quantity of WTR	• Higher sintering temperature may be required • May require solidification agent • Reduction in strength at higher WTR content
	Ceramics		• May be used as a pigment	• Can have an unwanted effect on colouration • Lower compressive strength • Greater shrinkage of products
Coagulant recovery and reuse	Recovery of metals/coagulant		• Reduction of WTR production • Has been economically viable in the past • Can recover >70% of coagulants	• Expensive due to chemical costs and processes involved • Not economically viable currently • Recovered coagulants are not as efficient as fresh coagulants
	Reuse in wastewater treatment		• Reduction of WTR production • Efficient removal rates • Reduces coagulant requirements for the process	• Regulations may limit use

Appendix 3 Combining WWTR and WTR for land application

Scottish Water produces sewage sludge (also known as Waste Water Treatment Residue; WWTR or biosolids) as a natural by-product of the wastewater treatment process. There are a number of sludge treatment centres employing various treatment techniques and manufacturing different biosolids (SW, 2020). In addition, nine further WTWW in Scotland are operated by Private Finance Investment (PFI) concessionaires. PFI concessions are generally the larger operational plants and treat 80% of sewage sludge generated in Scotland (Scottish Government, 2016). The Daldowie facility alone treats 40% of the national total. In 2017/18, the quantity of sludge generated was 120,032 t dry solids (tds), the majority of which came from the PFI assets – 106,292 tds – with 13,740 tds arising from Scottish Water-operated facilities (SW, 2020).

Approximately half of the costs of operating secondary sewage treatment plants in Europe can be associated with sludge treatment and disposal. Land application of treated sewage sludge can significantly reduce the sludge disposal cost component of sewage treatment as well as providing a large part of the nitrogen and phosphorus requirements of many crops (UN Food and Agriculture Organization, 2005).

The use of treated sewage sludge to land is an effective way of recovering value and avoiding waste. As such it is consistent with Scottish Government circular economy policy (see Appendix 2).

- It is a readily available alternative soil-building material.
- It contains nutrients and valuable trace elements essential to animals and plants.

It is a more sustainable alternative to inorganic fertiliser use in both agriculture and land restoration.

- It provides a good source of slow-release nitrogen ideal which is useful in land restoration.
- It is a good substitute for peat in land reclamation projects thus conserving valuable natural peatland (Scottish Government, 2016).

Recycling WWTR from the wastewater treatment process is one of the most sustainable ways of achieving a regenerative, circular economy that eliminates waste and enhances the environment (WaterWorld, 2021).

Regular applications of WWTR materials can improve water-holding capacity, drought resistance and structural stability, as well as the biological activity of soils. The greatest benefits are likely to be observed on soils where organic matter levels are low. Benefits of applying organic waste to soil depend on the properties of the waste and the receiving soil. Greatest risks occur where large quantities of waste containing high levels of potential pollutants are applied to the same land for many years (Cundill, 2012). There is a need for monitoring to identify extent of risk to ensure that farmers and contractors continue to follow good practice when applying organic material to land (ADAS, 2001).

Co-application of WWTR and water treatment residuals (WTR) land has not been extensively studied but may be beneficial by sorbing excess biosolid-borne or soil phosphorus (P) onto WTR, reducing the likelihood of off-site movement (Bayley 2008). Ippolito et al. (2002) indicate WTR could reduce P availability when co-applied with WWTR. Co-application can aid municipalities dealing with excessive WWTR-borne P and Mo application associated with a WWTR application rate that is selected to optimise nitrogen supply for the planned crop. However, if extractable phosphorus levels in soil are optimum or below optimum, high application rates of WTR may need to be avoided due to its adverse effect on P availability to plants, unless a supplemental P source is supplied. A study by Busalacchi (2012) investigated WWTR land treatments, which were applied alone, and in combination with a water treatment residual (WTR) and biochar (BC) in a "dream treatment" in storm water runoff plots. Addition of WTR to WWTR reduced soluble P compared to WWTR alone. Co-application of WTR with WWTR can reduce the build-up of P in soil as well as the risk of P losses to surface and ground water (Wang and Hu, 2013). However, application of WTR may result in P deficiency in soil and plant Al toxicity with increasing WTR rate and while co-application with WWTR may mitigate this to some extent, it may not fully counteract these negative impacts from the use of WTR, depending on soil conditions and the crop being grown. Increasing WTR application rate did not result in adverse effects on plant root growth (Wand and Hu, 2013).

Co-application of WTR and other organic amendments can increase positive impacts from the use of WTR in both agriculture and land restoration (Mahmoud and Ibrahim, 2012). A few studies examined crop yield impacts resulting from land spreading of co-applied or mixed WTR and WWTR. Mahdy et al. (2009) showed that the effective co-application ratio of WWTR to WTR for increasing corn yield and minimizing the potential for bioavailable P in runoff, was approximately 1:1 at the application rate of 3% WWTR and 4% WTR (equivalent to approximately 120 t ha^{-1}) in alkaline soils. Basta et al. (2016) explored the impact of applied WWTR/WTR mixtures on soil ecosystem services and found that these (i) improved soil quality, (ii) promoted rapid establishment of a dense and high-quality vegetation cover, placing a restored site on a trajectory towards establishment of native plant populations, and (iii) increased soil earthworm population and improved biodiversity of the terrestrial food web. The use of WTR can control dissolved P after vegetation is established, but application of WTR with more P sorption potential is needed than that used in Basta et al. (2016) study.

Appendix 4 Sorption and artificial soil mixtures

The capacity of WTR to reduce phosphorous availability (Gallimore et al., 1999; Agyin-Birikorang et al., 2009) could be used to remediate soils that are over-enriched with phosphorus or as a component of artificial soils (technosols, i.e., in landscaping or new-build housing gardens). WTR have been investigated for managing and restoring soils with excess nutrient levels or contamination (Turner et al., 2019).

Turner et al. (2019) summarised benefits and disbenefits of using WTR for sorption and land application (Table A3).

Some WTR, especially lime softening sludges (sludge resulting from the addition of limewater to remove hardness from water by precipitation), gained early attention as agricultural amendments to adjust soil pH (Elliott & Dempsey, 1991), as they are alkaline in nature. However, lime softening sludges are rarely produced in Scotland as most Scottish water used for drinking water supply is naturally soft.

WTR have potential to decrease availability of potentially toxic elements for uptake into plants, thus maintaining food quality (Tay et al., 2017). This ability, plus their already noted strong binding affinity for phosphorus, which can help to protect surface water and groundwater from phosphate-related eutrophication (Novak and Watts, 2004), have led to the development of WTR used as so-called technosol (artificial soil) substrates in the USA, either on their own or mixed with other materials such as composts or other fine aggregates to create an artificial topsoil.

Silveira et al. (2013) observed a decrease in leachate P concentration with application of Al-based WTR and suggested that soil disturbance due to incorporation of Al based WTR resulted in horizontal P transport in soil. The authors further concluded that the application of Al-WTR has no impact on cation accumulation by the plant roots, however suggestions were made to continuously monitor forage and soils to prevent nutrient deficiency after high rate or repeated Al-WTR application. They observed no further detrimental impact. Dayton & Basta (2001) evaluated the potential of 17 different WTR in USA as soil substitutes suitable for plant growth in land reclamation situations. In all cases, they found the nutritional content and availability suitable, apart from the availability of phosphorus. However, bioassay results indicated that levels of NO_2-N (generated by nitrification in the residue under aerobic conditions) were toxic to tomato seed germination in several of the WTR. Caniani et al. (2013) created a technosol mixture from WTR mixed with the stabilised organic fraction from municipal solid waste and investigated the potential for this substrate to be used as daily cover on landfill sites. The main advantage discovered was the low levels of leaching from the technosol material, especially with respect to elements responsible for eutrophication. Overall, it

Table A3. Benefits and disbenefits of using WTR for sorption and land application (Turner et al., 2019).

Potential market for end use	Benefits	Disbenefits
Constructed wetlands (sorption)	• High removal efficiencies • Proven success in incorporating bio-sorption reactors and microbial fuel cells	• Clogging • Low demand for WTR
Lakes and reservoirs (sorption)	• Could reduce chance of eutrophication through nutrient control	• Leaching of some elements still under question
Soil remediation (sorption)	• Can sorb high amounts of organic and inorganic pollutants • Reduction of P runoff could reduce eutrophication	• Potentially excessive P sorption • May require co-application to negate crop yield reduction in certain circumstances • Potential impacts relating to leaching of Al and Fe from coagulants
Bulk land application	• Increases aeration • Provides sufficient N for plant growth (although the quantities are not defined, provision of N could only be sufficient for a few years) • Can increase plant yield Increased hydraulic conductivity	• Excessive P sorption Co-application of P source may be required • Concerns regarding the leaching of metals

appears reasonable to conclude that the use of WTR in technosol mixtures, either for site restoration or for other applications such as landfill daily cover, provides a cost-effective outlet that also reduces usage of non-renewable natural resources such as topsoil.

In relation to the impact of using WTR on groundwater quality, Agyin-Birikorang et al. (2009) realised that groundwater total dissolved Al concentrations were unaffected by Al-WTR application, suggesting that Al-WTR could be safely used in a land-application programme without any negative impacts on groundwater (untreated ground pH=5.5 and WTR pH=5.6).

In summary, previous research has suggested that the agronomic benefits of WTR are limited and there is little direct impact on crop yield or quality. As such it is problematic to evaluate WTR as a soil amendment from an agricultural or economic standpoint. However, transportation cost is an important factor in selection of sites for receiving a specific WTR. Potentially more promising is the use of WTR in technosol mixtures for various geo-environmental applications. Low nutrient leaching, and in particular the affinity of WTR to bind P, make the material suitable for use in applications where water sources need to be protected.

The use of WTR as a technosol indirectly protects topsoil and is therefore likely to have wider environmental benefits and indirect protection of provisioning services. It is difficult to identify whether there is an economic benefit from using WTR as opposed to topsoil unless the change of practice also represents a reduction in carbon emissions. This would need to be investigated more fully. If it was found that the use of WTR in various geo-environmental applications was carbon beneficial, this could be a significant opportunity for WTR application, if effective government support for this could be developed.

Appendix 5. Decision Support Tool

Extracts of the MS Excel-based Decision Support Tool (DST) are given next page. The purpose of the tool is to screen potential spreading applications of WTR. The DST can be accessed on the CREW website (https://www.crew.ac.uk/) as a supporting document to this report.

Stage 1 WTR characteristics and initial screening

Stage 1.1: Stage 1.1 allows the WTR from a WTW to be compared with expected range arising from Scottish WTWs, and previous results from the individual WTW across a range of characteristics. The tool automatically flags any parameters out with the expected range for further investigation.

ACTION: Add WTR sample data into Column B

Stage 1.2: Identification of appropriate sites. This initial desk-based screening stage will use existing mapping data to help determine appropriate areas of Scotland's soils. Appropriateness will be based on key screening criteria and analysis of additional circular economy benefits. The screening criteria were developed based on the result of literature review and considerations expressed by PSG, where green criteria are physical and gold are circular economy.

The first step in the screening stage is the identification of farmer, landowner or restoration site willingness to accept WTR for spreading to land. It is anticipated that Stage 1.2 may only be needed when first establishing potential locations for a WTR arising from SW WTW as it will exclude less preferable locations for spreading, saving the time and cost required for site-based data collection.

The tool automatically flags any parameters out with expected range for further analysis (ADD). Plant tab avalaible for the future addition of individual WTW. **ACTION: Use the existing map links to support desk based screening.**

Stage 2 Identification of appropriate sites

Stage 2.1 Field Data Collection identifies information required to be collected on site and a description of the method of data collection. Following field data entry, the tool will identify based on pH and P level from SAC Interpretation whether it is likely WTR can be applied at this location. Other site considerations are also stated. **ACTION: Add field data findings to Column C, 2 green cells (rows 17 &18 indicate suitable location or not). Note need for SEPA risk Assessment.**

Stage 3 Benefit to final soil properties

Stage 3.1: This stage identifies the benefit of adding WTR to different land uses. The benefits are similar for each land use type, but the application rate and timescale for benefit are different.

Stage 3.2: This stage calculates the maximum application rate for the WTR data entered in Stage 1. It references the need for nutrients for 2 crop types and land reclamation to 20 cm.

The Decision Support Framework is a screening tool only. In this respect it can tell what is likely to be a maximum suitable spread rate based on the WTR. This tool cannot provide the expertise of an agriculture adviser, given that there are more land uses and recent soil analysis data needs to be taken into consideration when determining the application rate for a certain field.

ACTION: As part of the paragraph 7 exemption application an agricultural advisor should be engaged to determine application rate.

Stage 1.1 WTR characteristics and initial screening

Stage 1.1: WTR Characteristics		KEY:		<< data input required		
Parameter	Sample WTR Result (for input)	Within typical range (Y/N)	Typical SW Range (wtw / groupings) from 12 SW treatment plants		Typical international range (Turner et al. 2019)	Unit
			Lower Limit	Upper Limit		
Al	75600.00	YES	75600.00	222000.00	6700 - 180000	(mg kg^{-1} dry matter)
Fe		NO	4300.00	15150.00	1100 - 277000	(mg kg^{-1} dry matter)
P	190.00	NO	200.00	2500.00	200- 10000	(mg kg^{-1} dry matter)
Ca		NO	1000.00	3700.00	180 - 32000	(mg kg^{-1} dry matter)
Mn		NO	N/A	N/A	400 – 31600	(mg kg^{-1} dry matter)
Pb		NO	4.10	4.70	2.5 - 69	(mg kg^{-1} dry matter)
Zn		NO	15.00	722.00	0.12 - 246	(mg kg^{-1} dry matter)
Ni		NO	4.70	54.40	10.9 - 60	(mg kg^{-1} dry matter)
Cu		NO	6.00	153.00	35 - 624	(mg kg^{-1} dry matter)
Dry matter (DM) content		NO	21.40	26.20	N/A	%
N	4.00	YES	3.80	5.30	N/A	(kg fresh $tonne^{-1}$)
pH		NO	4.40	7.10	5.12 – 8.0	Unitless
Phosphate (P_2O_5)		NO	0.90	1.10	N/A	(kg fresh $tonne^{-1}$)
Potash (K_2O)		NO	0.07	0.12	N/A	(kg fresh $tonne^{-1}$)
MgO		NO	0.21	0.25	N/A	(kg fresh $tonne^{-1}$)
SO_3		NO	3.20	4.50	N/A	(kg fresh $tonne^{-1}$)
Readily available N		NO	0.06	0.12	N/A	(kg fresh $tonne^{-1}$)
RAN		NO	1.60	2.50	N/A	(% of total N)
Organic matter		NO	11.90	14.10	N/A	(% in fresh material)
Neutralising value (% CaO)		NO	1.00	2.30	N/A	Unitless
C:N ratio		NO	18:01	22:01	N/A	Unitless
Hg		NO	0.34	0.37	N/A	(mg kg^{-1} dry matter)
Cr		NO	10.10	15.00	N/A	(mg kg^{-1} dry matter)
Cd		NO	0.11	0.15	N/A	(mg kg^{-1} dry matter)
Se		NO	1.79	2.21	N/A	(mg kg^{-1} dry matter)
As		NO	11.40	13.50	N/A	(mg kg^{-1} dry matter)
Mo		NO	0.58	0.69	N/A	(mg kg^{-1} dry matter)
F		NO	418.00	505.00	N/A	(mg kg^{-1} dry matter)

Input data into column B
Columns D and E should be updated as required

Stage 1.1 Additional Sheets

Stage 1: WTR Characteristics (additional sheets as required)		KEY:		<< data input required
Parameter	Sample WTR Result (for input)	Within typical range (Y/N)	WTW (Name)	
			Lower Limit	Upper Limit
Al		YES		
Fe		YES		
P		YES		
Ca		YES		
Mn		YES		
Pb		YES		
Zn		YES		
Ni		YES		
Cu		YES		
Dry matter (DM) content		YES		
N		YES		
pH		YES		
Phosphate (P_2O_5)		YES		
Potash (K_2O)		YES		
MgO		YES		
SO_3		YES		
Readily available N		YES		
RAN		YES		
Organic matter		YES		
Neutralising value (% CaO)		YES		
C:N ratio		YES		
Hg		YES		
Cr		YES		
Cd		YES		
Se		YES		
As		YES		
Mo		YES		
F		YES		

Input data into column B
Columns D and E should be updated as required

Stage 1.2 Identification of appropriate sites

Stage 1.2: Identification of appropriate sites. This desk-based screening stage will use existing mapping data to determine appropriate areas of Scotland's soils. Appropriateness will be based on key screening criteria and analysis additional circular economy benefits		
	Screening Criteria*	Resource
2.1	Identification of willing landowners	SW database
2.2	Soil pH in acceptable range (>5.5)	http://www.ukso.org/static-maps/soils-of-scotland.html
2.3	P Sorption Capacity	https://soils.environment.gov.scot/maps/thematic-maps/map-of-soil-phosphorus-sorption-capacity/
2.4	Proximity to NVZ	https://soils.environment.gov.scot/maps/thematic-maps/map-of-soil-texture-in-nitrate-vulnerable-zones/
2.5	Proximity to Desingations	https://www.environment.gov.scot/our-environment/habitats-and-species/habitat-map-of-scotland/
		https://www.gov.scot/publications/shellfish-water-protected-areas-maps/
		https://www2.sepa.org.uk/bathingwaters/Locations.aspx
2.6	Proximinty to watercourse	SW GIS
2.7	Landuse and Crop	https://scotgov.maps.arcgis.com/apps/dashboards/f9216efc72e44b7e9093cfae08f6f861
	Circular Economy	
3.1	Acceptability - Proximity to population centres	SW GIS
3.2	Transportation Distance - (CO2 Equivalent /Cost)	SW GIS / database
3.3	Resource Recovery Value of resource recovery CO2 Equivalent	3.5 CO2eq. per tonne N in the product[#] (Benefit calculated in Stage 3.2)
[#]EU average, International Fertiliser Society, THE CARBON FOOTPRINT OF FERTILISER PRODUCTION:REGIONAL REFERENCE VALUES, Antione Hoxha and Bjarne Christensen(2019) ISBN 978-0-85310-442-1		
*Screening criteria is an indicative guide only to determine general areas where acceptable sites may be located.		

Stage 2.1 Data collection from chosen site

Stage 2.1: Data collection from chosen site to determine suitability of chosen site to receive WTR.

KEY:		<< data input required			
	Field Data Collection	Measured value	Units	Comments	Method
2.1	Soil pH	6	Unitless	Must be > 5.5	Sample from chosen site
2.2	P level[#]	30	mg/L	High	Sample from chosen site
2.3	Gradient		%	Steeper gradients will make application more challenging.	From observation or survey (contour maps)
2.4	Suitable storage location		N/A	Yes/No	Observation
2.5	Diatance of storage location to private water supplies		m	Contamination of water supplies possible if storage location is close to supply	From SW database/landowner/observation
2.6	Soil properties - particle size distribution		% Fine material (% c	Particle size provides a good estimate of soil hydraulic condictivity	Sample from chosen site (follow method outlined in ISO 17892-4)
2.7	Soil properties - hydraulic conductivity*		ms^{-1}	Soil hydraulic conductivity can be reduced with WTR spreading	Sample from chosen site/in-situ measurement
2.8	PTE -potentially toxic elements			Heavy metals are typically identified as Zinc (Zn), Copper (Cu), Nickel (Ni), Cadmium (Cd), Lead (Pb), Mercury (Hg), Chromium (Cr), Molybdenum (Mo), Selenium (Se), Arsenic (As) and Fluoride (F)	An example of is technical guidance provided by nrm laboratories: https://www.agrigem.co.uk/documents/AS18%20-%20Potentially%20Toxic%20Elements%20in%20Agricultural%20Soil.pdf for a list of PTEs and the maximum permissible concentrations based on pH range and maximum permissible averages over a 10-year period. These limits are a guide for all waste materials, and that would include WTR.
2.9	Sulphur		mg kg-1	WTR is unsuitable for use with soils with pH <5.5 and in soils high in extractable sulphur. Typically, this value is extractable sulphur > 50 mg kg^{-1}. Testing before WTR application to ensure the extractable sulphur is below this threshold value and the pH value is above 5.5 can lower the likelihood of Al toxicity.	Testing methods for total sulphur content in soil can be found in BS1377-3:2018.
3	Nitrogen		mg kg-1	Depending how much is present in the waste the N content can determine the WTR application rate.	The Modified Kjeldahl method for determining total Nitrogen in soil is outlined in ISO 11261:1995.

*Hydraulic conductivity can be estimated from particle size distribution, measured in falling head/constant head lab test or measured in falling head or rising head field test

[#]Descriptions of P level based on SAC Modified Morgans descriptions

**https://www.earthworksturf.com/pdf/soiltest/Standard_Soil_Test_Guidelines.pdf

Can WTR be applied at this location based on 2 key paramteters - pH, P (Note need for SEPA risk Assessment)	**Soil pH is acceptable and P level is high**

Stage 3.1 Summary of benefits.

Potential benefits of applying WTR to land	Potential disbenefits of applying WTR to land
• Improving hydraulic conductivity. • Increasing P storage capacity. • Increasing porosity. • Supplying nutrient elements such as K, N, S and Mg. • Possibly supplying P, if not readily desorbed. • Improving soil physicochemical properties (i.e., pH, electrical conductivity, water holding capacity, cation exchange capacity, organic matter content and soil aeration). • Controlling runoff pollution and/or phytotoxicity of heavy metals. • Absorbing organic and inorganic pollutants (less understood). • Enhancing nutrient recycling in agricultural soils. • Improved performance of plant root system. • WTR is successful if separate applications of vermicompost and poultry litter are made. • Successful application for land restoration.	• Unsuitable for soils with pH < 5.5, due to high Al content and increasing toxicity of Al at lower soil pH. • Decreasing available phosphorous and • deficiencies in plant tissue due to sorption – by Al and Fe oxides. • May require other types of fertilisers to be spread separately to negate crop yield reduction caused by phosphorus sorption. • Some WTR contain high levels of fine particles, therefore are unsuitable for agricultural land spreading where fine-textured soils are present as this may reduce soil porosity. • Commonly require dewatering prior to transportation which entails additional carbon emissions. Though, if transported without de-watering, this can increase the carbon footprint. • May not contain sufficient/right balance of nutrients to support good crop growth.

Stage 3.2 Application Rate

Stage 3.2 Indicative Application Rates calculated from Stage 1 for exemplar crops

	Input from Stage 1	spring barley		2-cut grassland	
	WTR	need in kg/ha	application rate t/ha	need in kg/ha	application rate t/ha
organic matter (kg/t)	0.00	n/a		n/a	
total N (kg/t)	4.00	130	32.50	210	52.50
total P2O5 (kg/t)	0.00	50	#DIV/0!	59	#DIV/0!
total K2O (kg/t)	0.00	52	#DIV/0!	210	#DIV/0!
Recovery C02 Equivalent 3.5 CO2eq. per tonne N saved			113.75		183.75
Benefit			suffcient N & P, limited K benefit		suffcient N & P, limited K benefit

References:

N need grassland	TN726, table F2: N grassland	https://www.fas.scot/publication/technical-note-tn726-fertiliser-recommendations-for-grassland/
N need barley	TN731, N residue group 1	https://www.fas.scot/publication/technical-note-tn731-nitrogen-recommendations-for-cereals-oilseed-rape-and-potatoes/
P&K need grassland	TN2016-18, table K	https://www.fas.scot/publication-type/technical-notes/page/4/
P&K need barley	TN716-18, table L (average between grain only or with straw)	

Regulation limit of other parameters to be considered
250kg/ha N
0.15 kg/ha Cd
15 kg/ha Cr
7.5 kg/ha Cu
0.1 kg/ha Hg
3 kg/ha Ni
15 kg/ha Pb
15 kg/ha Zn
0.7 kg/ha As
20 kg/ha F
0.2 kg/ha Mo
0.15 kg/ha Se

Appendix 6. Soil and WTR testing parameters

Below is a table of parameters that should be tested before application of WTR to soil. Regular testing before additional application is also recommended to ensure that these threshold values are not exceeded. Annual soil testing is common practice in similar circumstances and is recommended as a precautionary measure. The sampling regime should ensure that the data captures representative properties for the entire site, i.e., sampling frequency should be increased when the soil properties are variable across the specified site. Sampling should also be consistent in depth across all the samples. Samples taken in subsequent years should be taken from the same location (taking GPS coordinates of sample location may be useful to ensure consistency). Samples should be a minimum of 1 kg of soil to allow sufficient quantities to test. Roots/plants/cobbles etc., should be removed and not counted towards the total sample mass.

Table A4. Soil testing parameters

Parameter	Comments
pH	pH testing should be carried out in accordance with BS ISO 10390:2021. pH levels should be monitored to ensure the application of WTR does not reduce the overall pH of the receiving soil below 5.5 which can increase the likelihood of Al toxicity.
Phosphorus	Regular testing will ensure that P levels are maintained to allow sufficient plant available P. Typically, Scottish soils are more acidic than the UK average, and therefore the standard SAC test (Modified Morgan's solution) (Sutherland, 2019) is more appropriate for determining P levels. However, in soils where pH is greater than 7, or where soil is more calcareous, the bicarbonate Olsen test method may be more appropriate.
P sorption capacity	P sorption capacity can be estimated using maps provided by the James Hutton institute: https://map.environment.gov.scot/Soil_maps/?layer=16. Sorption capacity is given as either low (PSC1), moderate (PSC2) or high (PSC3).
Sulphur	WTR is unsuitable for use with soils with pH <5.5 and in soils high in extractable sulphur. Typically, this value is extractable sulphur > 50 mg kg^{-1}. Testing before WTR application to ensure the extractable sulphur is below this threshold value and the pH value is above 5.5 can lower the likelihood of Al toxicity. Testing methods for total sulphur content in soil can be found in BS1377-3:2018.
Nitrogen	Depending how much is present in the waste, the N content can determine the WTR application rate. The 'Modified Kjeldahl' method for determining total nitrogen in soil is outlined in ISO 11261:1995.
PTEs	Heavy metals are typically identified as Zinc (Zn), Copper (Cu), Nickel (Ni), Cadmium (Cd), Lead (Pb), Mercury (Hg), Chromium (Cr), Molybdenum (Mo), Selenium (Se), Arsenic (As) and Fluoride (F) These elements occur naturally in many soils, in different concentrations but most concern is about the accumulation of these elements in soils by the addition of manures, slurries and waste products. These levels should be tested before and regularly monitored after the application of WTRs. An example of technical guidance is provided by nrm laboratories: https://www.agrigem.co.uk/documents/AS18%20-%20Potentially%20Toxic%20Elements%20in%20Agricultural%20Soil.pdf for a list of PTEs and the maximum permissible concentrations based on pH range and maximum permissible averages over a 10-year period. These limits are a guide for all waste materials, and that would include WTR.

The table below lists WTR parameters that should be tested by an accredited laboratory. The table includes typical parameters analysed and those that are required for any paragraph 7 exemption are noted. Particle size distribution should be analysed following method outlined in ISO 17892-4:2016.

Table A5. WTR parameters		
Parameter	**Unit**	**Additional comments**
pH	Unitless	Required by SEPA for any paragraph 7 exemptions
Dry matter (DM) content	%	Required by SEPA for any paragraph 7 exemptions
Organic matter	(% in fresh material)	Required by SEPA for any paragraph 7 exemptions
N (Total)	(kg fresh $tonne^{-1}$)	Required by SEPA for any paragraph 7 exemptions
P (Total)	(mg kg^{-1} dry matter)	Required by SEPA for any paragraph 7 exemptions
Oxalate Extractable Phosphorus	(mg kg^{-1} dry matter)	The calculation of P-saturation ratio (PSR), degree of P-saturation DPS, and soil (here waste) P storage capacity (SPSC) PSR = P(oxalat) [mol] / (Fe(oxalat) [mol] +Al(oxalat) [mol]), DPS [%] = (P(oxalat) [mol] / (Fe(oxalat) [mol] +Al(oxalat) [mol])) * 100 SPSC [mg/kg] = (threshold – PSR) * (Fe(oxalate) [mol]] + Al(oxalate) [mol]) * 31 [mg/kg] (Nair, 2014).
K (Total)	(mg kg^{-1} dry matter)	Required by SEPA for any paragraph 7 exemptions
Mg (Total)	(mg kg^{-1} dry matter)	Required by SEPA for any paragraph 7 exemptions
S (Total)	(mg kg^{-1} dry matter)	
SO_4^{-2}	(mg kg^{-1} dry matter)	
Readily available N	(kg fresh $tonne^{-1}$)	Required by SEPA for any paragraph 7 exemptions
Neutralising value (% CaO)	Unitless	If it has neutralization capacity - Required by SEPA for any paragraph 7 exemptions
C:N ratio	Unitless	
Hg (Total)	(mg kg^{-1} dry matter)	Required by SEPA for any paragraph 7 exemptions
Cr (Total)	(mg kg^{-1} dry matter)	Required by SEPA for any paragraph 7 exemptions
Cd (Total)	(mg kg^{-1} dry matter)	Required by SEPA for any paragraph 7 exemptions
Se (Total)	(mg kg^{-1} dry matter)	
As (Total)	(mg kg^{-1} dry matter)	
Mo (Total)	(mg kg^{-1} dry matter)	
F (Total)	(mg kg^{-1} dry matter)	
NO^-_2 (nitrite)	(mg kg^{-1} dry matter)	Mentioned in the report as a potential issue (Tables 9, 10)
Al (Total)	(mg kg^{-1} dry matter)	Required by SEPA for any paragraph 7 exemptions
Fe (Total)	(mg kg^{-1} dry matter)	Required by SEPA for any paragraph 7 exemptions
Ca (Total)	(mg kg^{-1} dry matter)	
Mn (Total)	(mg kg^{-1} dry matter)	
Pb (Total)	(mg kg^{-1} dry matter)	Required by SEPA for any paragraph 7 exemptions
Zn (Total)	(mg kg^{-1} dry matter)	Required by SEPA for any paragraph 7 exemptions
Ni (Total)	(mg kg^{-1} dry matter)	Required by SEPA for any paragraph 7 exemptions
Cu (Total)	(mg kg^{-1} dry matter)	Required by SEPA for any paragraph 7 exemptions

CRE W CENTRE OF EXPERTISE FOR WATERS

CREW Facilitation Team

Hydro Nation International Centre

James Hutton Institute

Craigiebuckler

Aberdeen AB15 8QH

Scotland UK

Tel: +44 (0)344 928 5428

Email: enquiries@crew.ac.uk

www.crew.ac.uk

Hydro Nation International Centre

The James Hutton Institute

Scottish Government Riaghaltas na h-Alba gov.scot

CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes and Research Institutes. The Centre is funded by the Scottish Government.