Managing phosphorus in the UK water industry to increase national resource security

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ABSTRACT

Phosphorus is an essential, irreplaceable component of the food production system. Most of the phosphorus applied in agriculture comes from phosphate rock, a finite, non-renewable resource. Therefore, there are growing concerns about global phosphorus scarcity and the sustainability of modern agriculture.

The aim of this research was to determine if the UK water industry will be required to increase the amount of phosphorus that is recycled from wastewater.

This research involved conducting an extensive literature review and gathering data from secondary sources, which was then analysed to address the guiding research questions.

This analysis suggests that phosphorus recycling could be increased, but changes to existing legislation and infrastructure will be required. The substance flow analysis revealed that the water industry is a key stakeholder in UK phosphorus management, and the intensifying geopolitical risk to security of supply suggests that increased phosphorus recycling will be required in the near future. Finally, a Phosphorus Recycling Obligation scheme was developed as a means of optimising investments and achieving recycling targets.

It is concluded that the UK water industry will be required to increase the amount of phosphorus that is recycled from wastewater in the near future in order to address national resource security.

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Efficiency	The ratio of outputs to inputs to a system or process. Normally expressed as a percentage.
Geopolitics	The combination of geography and politics, which relates especially to international politics that affects the whole world.
Mineral fertilisers	Fertilisers derived from phosphate rock. Also sometimes referred to as inorganic fertilisers.
Organic fertilisers	Fertilisers derived from organic wastes such as food waste, human waste and sewage sludge.
Phosphate	Refers to phosphorus in fertilisers, expressed as P_2O_5.
Phosphate rock	Typically refers to phosphate rock concentrate, which has been upgraded through a beneficiation process to reach a marketable standard. Phosphate rock as ‘ore’ is qualified wherever this is used. This can be either sedimentary or igneous rock.
Phosphorus	Elemental phosphorus.
Recovery (P recovery)	Processes that are specifically designed to extract valuable products from wastewater, sewage sludge or incineration ash.
Recycling (P recycling)	Refers principally to applying phosphorus from secondary sources to agricultural land, although other uses, such for industrial applications, are also considered as recycling.
Removal (P removal)	Specific processes (chemical or biological) that are designed to remove phosphorus from wastewater above normal treatment standards.
Renewable P	All forms of secondary, recycled or recovered phosphorus are considered as renewable. Phosphate rock is a primary source that is non-renewable.
Resilience	The ability of a system to resist or recover from disturbance.
Scarcity (resource scarcity)	When supply cannot meet human demand due to any number of factors, within a given boundary of time and space.
Security (security of supply)	A supply that is reliable, available, resilient, affordable, and sustainable.
Strategy	A plan of actions required to achieve a specific goal or result.

Sustainable development	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.
Timeframe (short, medium and long term)	Short term < 25 years. Medium term = 50 years. Long term =/> 100 years.
Water companies	Refers specifically to the companies that treat both water and wastewater.
Water industry	Refers specifically to the water and wastewater industry in the UK, which consists of 12 water companies.

LIST OF ABBREVIATIONS

ACHS	Advisory Committee on Hazardous Substances
AD	Anaerobic Digestion
AMP	Asset Management Plan
AS	Activated Sludge
ATP	Adenosine Triphosphate
BGS	British Geological Survey
BOD	Biochemical Oxygen Demand
BP	British Petroleum
BPEO	Best Practicable Environmental Option
CaP	Calcium Phosphate
CCC	Committee on Climate Change
CEEP	Centre Européen d'Etudes des Polyphates
CfD	Contract for Difference
CIWEM	Chartered Institution of Water and Environmental Management
CRC	Carbon Reduction Commitment
DECC	Department of Energy & Climate Change
Defra	Department for Environment, Food and Rural Affairs
DNA	deoxyribonucleic acid
EA	Environment Agency
EBPR	Enhanced Biological Phosphorus Removal
EC	European Commission
ESPP	European Sustainable Phosphorus Platform
ETS	Emissions Trading Scheme
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
FiT	Feed in Tariff
GPRI	Global Phosphorus Research Initiative
HaP	Hydroxyapatite
IFA	International Fertilizer Industry Association
IFDC	International Fertiliser Development Centre
kt	kilo tonnes (thousand tonnes)
MAP	Mono-Ammonium Phosphate (not magnesium ammonium phosphate, which is referred to as struvite)
MDG	Millennium Development Goal
MFA	Material Flow Analysis
MHa	Million hectares
Mt	Million tonnes
MWh	Mega Watt hours

NVZs	Nitrate Vulnerable Zones
OCP	Office Chérifien des Phosphates
ONS	Office for National Statistics
P	Production (when used in the context of R/P ratios)
P	Phosphorus
p.e.	population equivalent
PR	Phosphate Rock
PR	Price Review
PRO	Phosphorus Recycling Obligation
PROCs	Phosphorus Recycling Obligation Certificates
R	Reserves (when used in the context of R/P ratios)
R/P	Reserve-to-Production ratio
RO	Renewables Obligation
ROCs	Renewables Obligation Certificates
SDSs	Strategic Direction Statements
SFA(s)	Substance Flow Analysis (Analyses)
SNIFFER	Scotland & Northern Ireland Forum for Environmental Research
TSP	Triple Superphosphate
UKWIR	UK Water Industry Research
UN	United Nations
UNEP	United Nations Environment Programme
URR	Ultimate Recoverable Resource
USBM	United States Bureau of Mines
USGS	United States Geological Survey
UWWTD	Urban Waste Water Treatment Directive
VFAs	Volatile Fatty Acids
WAS	Waste Activated Sludge
WFD	Water Framework Directive
WFS	World Food Summit
WMW	Waste Management World
WwTWs	Wastewater Treatment Works

1 INTRODUCTION

The element phosphorus (P) was discovered in 1669 by Henning Brandt, a German alchemist, whilst searching for the philosopher's stone (Emsley, 2001). In 1840, Justus von Liebig confirmed that phosphorus has a fertilising effect on plant growth (Ashley et al., 2011), and, in accordance with Liebig's Law of the Minimum a lack of phosphorus would limit plant growth (Roy et al., 2006). It is now known that phosphorus plays an irreplaceable role within all living cells, found within cell membranes, ATP and DNA. Because of its ability to affect plant growth, phosphorus can be considered as a both a pollutant and a resource.

When used for agricultural purposes, phosphorus is an essential resource that boosts crop yields. Applying regular applications of fertilisers to agricultural land is necessary to increase soil fertility and replace the phosphorus that is removed within harvested crops or lost through fertiliser runoff and soil erosion. Traditionally, farmers applied organic fertilisers from recycled wastes such as animal manure and human wastes. These recycled wastes are referred to as secondary resources. However, since around 1847, mineral fertilisers have been manufactured from primary sources, such as guano (bird droppings that have accumulated over thousands of years) (CIWEM, 2012), Thomas slag (a waste product from the steel industry) (de Haes et al., 2009), and, since 1850, from rocks rich in phosphate minerals (mostly apatite), which are collectively known as phosphate rock. Today, following the depletion of most guano deposits (Filippelli, 2011), phosphate rock represents the major, and only new raw material supply for fertiliser production (UNEP, 2011). It is estimated that around 60% of the phosphorus applied to the world's agricultural land now comes from phosphate rock (Cordell, 2010, Liu et al., 2008, Smil, 2000, Smit et al., 2009), with the remainder from recycled, secondary sources, such as animal manure, human excreta and crop residues. The use of phosphate rock as a primary source of fertilisers is effectively transferring phosphorus from the geological, inorganic phosphorus cycle, which takes millions of years, to the faster moving land-based and water-based organic phosphorus cycles. The use of phosphate rocks has increased the amount of phosphorus circulating within the anthropogenic phosphorus cycle, allowing agricultural systems to produce enough food to support a rapidly growing population.

The use of mineral fertilisers combined with other improvements in agricultural practices has increased agricultural productivity. Because of this, the limit to population growth as a result of widespread famine, disease and/or war, which was postulated by Thomas Malthus in 1798, has so far been avoided (Malthus, 1798). As shown in Figure 1, the size of the world's population has increased rapidly since that time, from 1 billion in the year 1800, to 1.7 billion in 1900 and 6.1 billion by the year 2000 (UN, 1999). The global population is now estimated at 7.2 billion people (UN, 2013b).

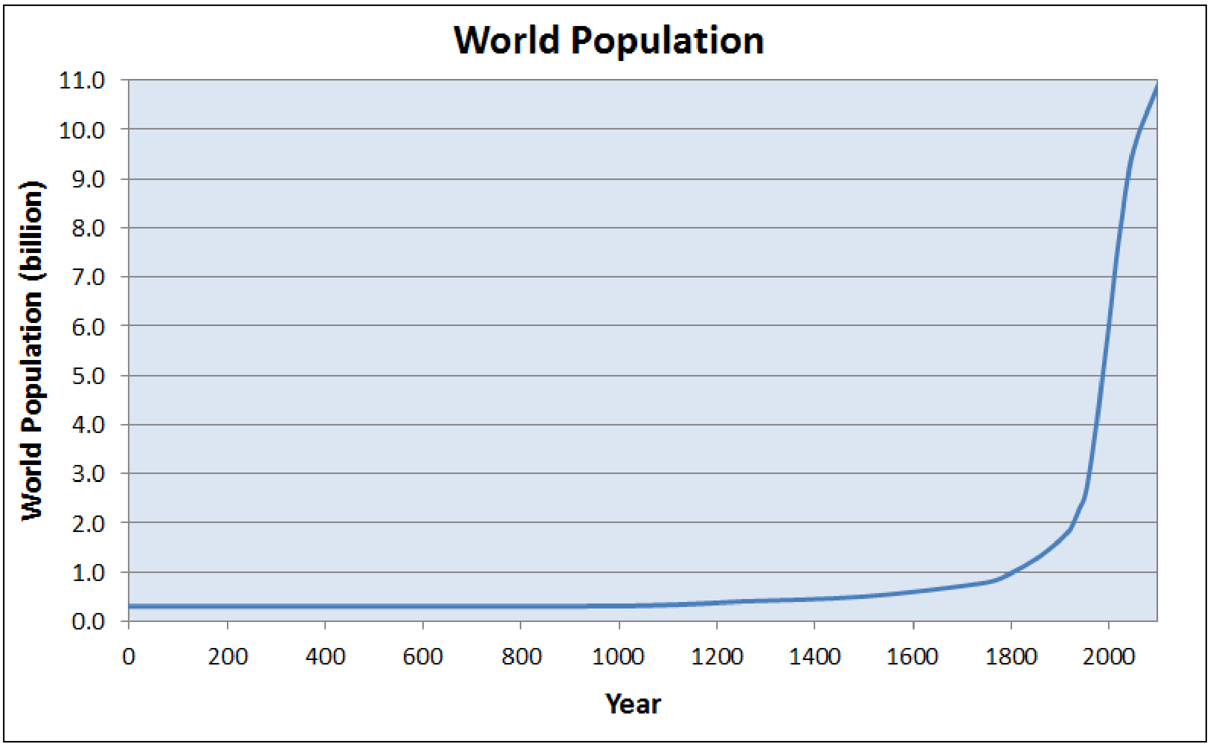


Figure 1: World Population from the Year 0 to 2100.

Data Source: UN (1999) for years 0 – 2000, and UN (2013b) medium variant for years 2013 to 2100.

This rapid population growth was made possible by increased food production, which required increased resource inputs, including phosphorus derived from phosphate rock. As a result, phosphate rock production has increased from around 3 million tonnes (Mt) in 1900 (Buckingham and Jasinski, 2012) to around 224 (Mt) In 2013 (Jasinski, 2014), and it is estimated that around 90% of the phosphorus derived from phosphate rock is used in agriculture (Brunner, 2010).

The continued growth in population, which is projected to reach 9.6 billion by 2050 and 10.9 billion by 2100 (UN, 2013b), will require increased food production. In fact, it has been estimated that the continued rising population and changing diets will require approximately 70% more food to be produced by 2050 (Foresight, 2011). To further increase food production, modern agriculture will require increased amounts of fertilisers containing phosphorus, most of which will be derived from phosphate rock.

The European Commission defines sustainability as the “use of resources at rates that do not exceed the capacity of the Earth to replace them” (EC, 2013b). Therefore, food production systems that are dependent on the continued and increased extraction of finite and non-renewable resources, such as phosphate rock, are not sustainable and cannot continue indefinitely. Because of this, there are now growing concerns about future phosphorus supplies and the ability of modern agricultural systems to sustain or increase food production in the future to meet the demands of a growing population. Consequently, phosphorus and phosphate rock are increasingly included in assessments of resources critical to the UK and European economics, as shown in Table 1, including the recent addition to the European Commission’s list of raw materials critical to the EU (EC, 2014).

Table 1: Recent assessments of resource security

Report / Study	Description	Includes phosphorus?
Material Security - Ensuring resource availability for the UK economy. (Oakdene Hollins, 2008)	The Oakdene Hollins report to the Resource Efficiency Knowledge Transfer Network assesses material insecurity for the UK, based on eight basic criteria (four material risks and four supply risks) A total of 69 materials were assessed, although phosphorus was not included in this analysis.	No
Critical raw materials for the EU. (EC, 2010a)	Within a review of critical raw materials, the EU defined a 'critical material' as having high access, supply or environmental risks. Based on a defined method of assessing criticality, the working group assessed 41 raw materials, including iron, aluminium, copper, chromium, tungsten and rare earths, and produced a list of 14 critical raw materials. Phosphorus or phosphate rock was not included in this assessment. Phosphate rock was later included in the 2013 assessment.	No
Review of the Future Resource Risks Faced by UK Business and an Assessment of Future Viability. (AEA, 2010)	The AEA report analyses the material supply and demand risks for UK businesses, and highlight six key resources (aggregates, fish, indium, lithium, rare earth elements and phosphorus). Phosphorus is highlighted as a risk for UK agriculture. It suggests that investment in phosphorus recovery technologies will be important in the future, and that changes to regulation are required to ensure recovered materials are used as products, rather than wastes. Also, it was suggested that farmers should seek to use increased amounts of recovered phosphate to reduce reliance on non-renewable inputs.	Yes
Reinventing the wheel - A circular economy for resource security. (Hislop and Hill, 2011)	Examined three crucial inputs to society (metal, water and phosphorus) and recommended a range of economic measures such as a phosphate tax or levy and financial incentives to encourage the use of secondary sources of phosphorus and develop a circular economy for phosphorus.	Yes

Raw materials critical to the Scottish Economy. (SNIFFER, 2011)	The SNIFFER report draws heavily from the AEA report, but increases the number of resources analysed. A traffic light system is used to demonstrate the assessment of supply and demand risks. Phosphorus is given a red (high risk), for both supply and demand, indicating an increasing demand and reducing supply or supply issues, and is therefore given a red for overall assessment.	Yes
British Geological Survey - Risk list 2012. (BGS, 2012)	The British Geological Survey (BGS) produces a list of chemical elements or element groups which are required to maintain our economy and lifestyle. This assessment is based on abundance, location of production and reserves, and political stability producing countries. Around 40 elements are included on the list, with rare earth elements at the top of the list. Phosphorus is not included.	No
Report on critical raw materials for the EU. (EC, 2014)	Phosphate rock was added to the 2013 assessment of critical raw materials for the EU. The list now includes 54 materials, and phosphate rock was also included as one of 20 critical raw materials.	Yes

A system or practice that is unsustainable, such as the extraction of non-renewable resources, will eventually result in scarcity. Scarcity is when the supply is unable to meet demand due to any number of factors, within a given boundary of time and space (Cordell, 2010). Global phosphorus scarcity would affect the UK agricultural industry and food supply. To reduce this risk, it is necessary to increase security of supply. Defra’s Resource Security Action Plan (Defra, 2012e) states that security of supply relates to a combination of:

a) Physical risks – such as the reduced accessibility of resources as the quality of ore decreases, and temporary shortages resulting from increases in production lagging behind increases in demand.

b) Geopolitical risks – such as the concentration of production in a small number of countries, and restriction on trade.
c) Economic risks – such as price volatility and rising prices, which are influenced by physical and geopolitical risks.

Cordell (2010) defines global phosphorus security as ensuring that "all the world's farmers have access to sufficient phosphorus in the short and long term to grow enough food to feed a growing population, while ensuring farmer livelihoods and minimising detrimental environmental and social impacts." For the UK, phosphorus security is defined as ensuring the UK food production system has a supply of phosphorus that is available, reliable, resilient, affordable, sustainable, and has a low environmental and social impact. Each of these terms is defined below:

- **Available** – There is a sufficient physical quantity of phosphorus to support all farmers.
- **Reliable** – The supply of phosphorus is assured over time.
- **Resilient** – The supply of phosphorus is able to resist disruptions, or recover quickly from any disruption.
- **Affordable** – The cost of fertilisers is acceptable for farmers to sustain their livelihoods and profitable business without increasing food prices.
- **Sustainable** – The long-term supply of phosphorus is guaranteed.
- **Low environmental and social impact** – the supply does not result in environmental damage (climate change, water pollution etc.) or have negative impacts to society (human health etc.).

Although the Resource Security Action Plan does not specifically mention phosphorus, it does state that sustainable development and security of supply can be increased by "using as much recycled and secondary material as possible" (Defra, 2012e). Therefore, to increase the sustainability and security of food production, agricultural systems will need to increasingly utilise renewable, secondary sources of phosphorus in the future. This includes phosphorus recycled from organic wastes such as animal manure and sewage sludge. For the UK, which has no phosphate rock reserves of its own, developing renewable alternatives will also reduce the current reliance on imported resources and increase security of supply. Since most of the phosphorus consumed within human food ends up in wastewater, which is then treated by wastewater treatment systems, this suggests that the UK water industry could become a key stakeholder in a future resource management system for phosphorus in the UK.

However, the UK water industry has traditionally managed phosphorus within wastewater as a pollutant, rather than a resource. This is because, as well as having a fertilising effect on agricultural plants, phosphorus also increases growth of algae and aquatic plants when it enters water systems. This increased nutrient loading to aquatic ecosystems, known as eutrophication, has a detrimental impact on the ecosystem, including depletion of oxygen supplies, elevated pH and reduced biodiversity, as well as negative impact on ecosystem services, such as the provision of drinking water and recreation activities (Smith et al., 1999, Millennium Ecosystem Assessment, 2005). In fact, out of all other nutrients, phosphorus is considered to be the principal driver for eutrophication in lakes and estuaries (Millennium Ecosystem Assessment, 2005), and phosphorus has also been identified as the main cause for failing to meet water quality objectives for UK inland surface waters set under the EU

Water Framework Directive (ESPP, 2013c). European legislation, such as the Urban Waste Water Treatment Directive (UWWTD) (The Council of the European Communities, 1991b) and the Water Framework Directive (WFD) (The European Parliament and the Council of the European Union, 2000), has required enhanced levels of phosphorus removal to be achieved at UK wastewater treatment works, above the level that would be achieved through conventional wastewater treatment processes. Therefore, specific phosphorus removal processes have been installed at many UK wastewater treatment works. By 2015, it is expected that 639 WwTWs, serving a population equivalent to 23 million people, will have installed phosphorus removal processes (UKWIR, 2010). Furthermore, it is estimated that a further 2,000 WwTWs may require phosphorus removal processes to meet water quality standards (Environment Agency, 2012).

The increasing demand to remove phosphorus from wastewater to reduce environmental pollution coincides with an increasing awareness of phosphorus as a critical resource. This presents the opportunity to couple increased phosphorus removal to reduce environmental pollution, with increased phosphorus recycling to contribute towards a more sustainable food production system and phosphorus security for the UK. However, there is currently no requirement for the UK water industry to increase the amount of phosphorus that is recycled from wastewater.

The aim of this thesis is to determine if the UK water industry will be required to increase the amount of phosphorus that is recycled from wastewater in the future in order to address national resource security. This research was sponsored by all 12 UK water companies who provided information and guided the research through three steering group meetings.

1.1 Thesis Structure

This thesis is guided by the following research question:

Will the UK water industry be required to manage phosphorus as a resource in the future, and could an increase in phosphorus recycling from wastewater contribute to phosphorus security in the UK?

Addressing this research question forms the main Aim of this thesis. In order to answer this overall guiding question, the following questions must first be addressed:

1) How does the UK water industry currently manage phosphorus? What are the key challenges associated with increasing phosphorus recycling from wastewater?
2) Why would the water industry be targeted to increase phosphorus recycling to address national resource security? How much phosphorus is found within wastewater and how does this compare to phosphorus flows in other wastes?
3) When would an increase in phosphorus recycling from wastewater be required to increase UK phosphorus security? What are the key drivers of global phosphorus scarcity and the timescales associated with each?
4) What strategy could be developed to encourage the UK water industry to manage phosphorus as a resource, and how would the industry respond to such as strategy? What impact would an increase in phosphorus recycling have on resource security?

These four guiding questions are translated into the four Objectives of this research, and will be addressed through a detailed, critical analysis of existing literature, and through further investigation and analysis of any identified knowledge gaps. Each section of this thesis contains four sub-sections which address the four guiding questions.

The thesis is split into the following sections:

Section 2 – Aims and Objectives. Sets out the overall aim of the further research, and the specific objectives that must be addressed to fulfil this aim.

Section 3 – Hypotheses. Establishes the hypotheses for each research question, which will be addressed through further research and analysis.

Section 4 – Literature review. Establishes the state-of-the-art knowledge that could be used to address each of the guiding questions. The knowledge gaps identified within the literature review will be developed into the aims and objectives of this research.

Section 5 – Methodology. Outlines how each of the hypotheses will be tested.

Section 6 – Results and Analysis. Presents the key results and analyses for each section.

Section 7 – Discussion. Discusses the importance of the results and how this new information addresses the research questions.

Section 8 – Conclusions. Concludes the thesis with remarks for each section of the thesis, as well as a conclusion to the overall guiding question.

Section 9 – Recommendations. Establishes recommendations for improving phosphorus management within the UK water industry to address security of supply for the UK. Also includes any further research requirements that were identified throughout this research.

2 AIMS AND OBJECTIVES

2.1 Aim

The aim of this research is to determine if the UK water industry will be required to increase the amount of phosphorus that is recycled from wastewater in the future in order to address national resource security.

2.2 Objectives

The specific objectives are to:

1. Evaluate the current position of the UK water industry in terms of phosphorus management practices, relevant legislation, existing infrastructure and the compatibility with technological options to increase phosphorus removal, recovery and recycling from wastewater.
2. Construct a detailed substance flow analysis to map phosphorus movements within the UK, including the major flows, accumulations and losses, and quantify the amount of phosphorus within wastewater compared to other phosphorus flows within the UK.
3. Analyse the global phosphorus situation and evaluate the key drivers of scarcity which could affect phosphorus security in the UK and drive the need for increased recycling of phosphorus from wastes such as wastewater and sewage sludge.
4. Create and evaluate a plausible resource management strategy for phosphorus in the UK water industry, considering the risks and opportunities, the industry response, the impact on individual water companies and the effect on UK phosphorus security.

3 HYPOTHESES

1) Changes to current legislation, existing infrastructure and treatment methods will be required to significantly increase phosphorus recycling from wastewater.
2) There are sufficient quantities of phosphorus within wastewater compared to other waste streams in the UK for the water industry to be considered as a key stakeholder in UK phosphorus management and will therefore be required to play a significant role in increasing phosphorus security.
3) The risks to security of supply will result in the requirement for the water industry to increase phosphorus recycling from wastewater in the near future.
4) A renewable phosphorus strategy introduced within the water industry would encourage investments in phosphorus removal, recovery and recycling technologies, which would significantly increase the amount of phosphorus that is recycled from wastewater and make a large contribution towards national resource security.
5) The UK water industry will be required to begin managing phosphorus as a resource in the near future, and increased phosphorus recycling from wastewater could make a significant contribution to UK resource security.

4 LITERATURE REVIEW

The purpose of this literature review is to establish the current knowledge relating to the guiding questions in Section 1.1, as well as identifying any knowledge gaps that require further research or analysis. This review is split into the following sections:

1) The UK water industry – Establishing the current position of the UK water industry in terms of infrastructure, legislation, treatment type etc., and identifying the technological options that exist to recover and recycle phosphorus from wastewater.
2) Quantifying phosphorus flows – Identifying the movement of phosphorus throughout the UK food production system, in order to quantify phosphorus flows within the water industry and compare these to other flows throughout the UK.
3) Drivers for phosphorus scarcity – Critically analysing the principal drivers for global phosphorus scarcity that could drive phosphorus as a resource issue in the UK water industry.
4) Resource management strategies – Evaluating resource management strategies for other resources, such as energy in the UK, or phosphorus in other countries.

4.1 The UK Water Industry

Guiding question: How does the UK water industry currently manage phosphorus?

In order to determine if the UK water industry will be required to increase the amount of phosphorus that is recycled from wastewater in the future, it is important to first establish how the water industry currently manages phosphorus. From this known position, it will be possible to determine if and how increased recycling of phosphorus could be achieved. Therefore, the purpose of this section is to critically evaluate the current position of the UK water industry in terms of phosphorus management. This will include an analysis of:

- The structure of the industry, including the size and location of the individual water companies that make up the whole industry, and the industry regulators.
- Important legislation relevant to phosphorus management.
- Phosphorus flows throughout the industry.
- Phosphorus removal technologies used to reduce the amount of phosphorus in the final effluent.
- Sewage sludge disposal methods.
- Phosphorus recovery technologies that can be used to produce a valuable product from wastewater.

4.1.1 Structure of the industry

The UK population is now (as of mid-2012) 63.7 million people (ONS, 2013) and, when combined with industry, produces around 11 billion litres of wastewater each day (Defra, 2012f). This wastewater generally contains less than 0.1% solid material, but would cause significant environmental damage if it was discharged to water systems without treatment (Defra, 2012f). Approximately 96% of the UK population are connected to wastewater treatment works (WwTWs) (Defra, 2012f), which can remove potentially damaging substances from their wastewater by settling out the solid matter (primary treatment), using bacteria to break down organic substances (secondary treatment) and employing additional methods to remove other pollutants such as phosphorus or nitrates (tertiary treatment) (Defra, 2002).

The WwTWs are owned by the UK water industry, which was privatised in 1989 (Water UK, 2013b). The industry now consists of 12 water and sewerage companies (shown in Figure 2), and 14 water suppliers (Water UK, 2013a). Since phosphorus recycling is mainly associated with wastewater, the terms 'the UK water industry' and 'the water companies' shall refer to the 12 water and wastewater companies listed in Table 2 and shown in Figure 2.

Table 2: The 12 UK water and wastewater companies

Country	Water Company
England	• Anglian Water
	• Northumbrian Water
	• Severn Trent Water
	• South West Water
	• Southern Water
	• Thames Water
	• United Utilities
	• Wessex Water
	• Yorkshire Water
Wales	• Welsh Water
Scotland	• Scottish Water
Northern Ireland	• Northern Ireland Water

Figure 2: A map of the UK water and sewerage companies.
Source: Water UK (Water UK, 2007)

The 10 water companies in England and Wales are privately owned, with Welsh Water (Dwr Cymru) operating as a not-for-profit company, while Scotland and Northern Ireland both a have a single service provider that is publically owned but relies on private companies to deliver many of its services (Water UK, 2013a).

The UK population is rapidly increasing, and is projected to reach 73.3 million by 2037 (ONS, 2013). This 15% population increase from 2012 to 2037 will significantly increase the volume of wastewater and phosphorus received at UK WwTWs. Assuming that each person uses and discharges 150 l of water and wastewater each day (Water UK, 2006b), then an additional 9.6 million people would generate an additional 1.4 billion litres of wastewater per day, which is a 12% increase on the 11 billion litres currently produced. The percentage increase in phosphorus load to WwTWs is expected to be similar to the increase in population, i.e. 15%, although there are several factors that affect this, including the size of industrial outputs, the use of detergents, and the increasing number of people connected to sewers. An understanding of future phosphorus flows to WwTWs would be useful to identify the future 'hot spots' for phosphorus removal and recovery, although no such study was found during this literature review.

The UK water industry is highly regulated in order to ensure that the companies carry out their responsibilities for water provision and wastewater treatment, whilst at the same time protecting customer interests (Water UK, 2013c). The price that companies can charge their customers is set by the Water Services Regulatory Authority (Ofwat) in England and Wales, the Water Industry Commission in Scotland, and the Utility Regulator in Northern Ireland (Water UK, 2013c). The industry currently operates in five-year price limit periods known as AMP (Asset Management Plan) periods (Defra, 2012d), where the industry's economic regulators conduct a price review (PR) process to determine the price that the water companies can charge their customers during these five year periods (Defra, 2012d). This is designed to protect customer interests whilst ensuring that the water companies can deliver the services require of them (Defra, 2012d). The current AMP period is the fifth cycle since privatisation in 1989, and is therefore known as AMP5, which runs from 2010 – 2015 (Defra, 2012d). As part of the 2009 price review process (PR09), the water companies were also required to produce 25-year Strategic Direction Statements (SDSs), which act as long term business plans which are supported by the 5-year AMP plans (Ofwat, 2012). The SDSs include plans for delivering key services, approaches to climate change and sustainability, details of managing major risks, and methods of financing these strategies with implications to customers' bills (Ofwat, 2012).

Since privatisation, the industry has invested huge sums of money modernising infrastructure. Some of these investments have been financed by increasing customer bills, which have risen faster than inflation, but also through outside investment (Water UK, 2013b). This has left the water industry with debts amounting to around £33bn, or around £1,500 per customer (Severn Trent Water, 2010). Capital investments over the next 20 years are estimated to cost an additional £96bn (Severn Trent Water, 2010).

The discharge of wastewater into river systems can cause environmental damage. The industry is therefore regulated on environmental impacts by the Environment Agency (EA) and Natural England in England and Wales, the Scottish Environment Protection Agency (SEPA) in Scotland, and the Northern Ireland Environment Agency (NIEA) in Northern Ireland (Water UK, 2013c).

The industry is represented at the national and European level by Water UK and British Water. Government policy and regulations that affect the water industry are mainly associated with the Department for Environment, Food and Rural Affairs (Defra) and the Department for Energy and Climate Change (DECC). UK Water Industry Research (UKWIR) facilitates collaborative research projects based on industry-wide issues.

4.1.2 Important legislation

The activities of the water industry have the potential to cause environmental damage, therefore the industry is highly regulated, with most UK regulations being derived from EU Directives (Water UK, 2013a). Identifying the main legislative drivers was suggested by Zakkour et al. (2002) as the first part in developing a sustainable energy strategy for a UK water company. Therefore, a similar review of existing legislation has been undertaken to identify the main legislative drivers that influence current phosphorus management practices and could affect future the development of a resource management system for phosphorus.

This section presents the review of important legislation. In terms of phosphorus discharges from WwTWs, the two most important pieces of legislation are the Urban Waste Water Treatment Directive (1991/271/EEC) (Section 4.1.2.1) and the Water Framework Directive (2000/60/EC) (Section 4.1.2.2). The industry also has to meet significant carbon reduction targets, as mentioned in Section 4.1.2.3. This section also considers phosphorus management legislation that is being discussed at the European level and could translate into a future phosphorus directive (Section 4.1.2.4). The practice of recycling sewage sludge to agricultural land is highly regulated, and this is discussed later in Section 4.1.4.

4.1.2.1 Urban Waste Water Treatment Directive

The Urban Waste Water Treatment Directive (UWWTD) (The Council of the European Communities, 1991b) is designed to protect the water environment and the use of water for drinking, recreation and industry (Defra, 2002). The Directive was adopted on 21st May 1991

(Defra, 2012f), and resulted in the publication of The Urban Waste Water Treatment (England and Wales) Regulations (1994).

The Regulations state that water and sewerage companies must now employ secondary biological treatment at all treatment works with a population equivalent (p.e.) greater than 2,000 p.e., and bans the disposal of sewage sludge to the sea. The Regulations also state that further tertiary treatment, which includes specific phosphorus removal processes, is required for works above a certain size that are discharging into ‘sensitive areas’. These sensitive areas are defined as areas that are eutrophic or at risk of becoming eutrophic, areas intended for drinking water abstraction that could exceed nitrate limits, and areas where further treatment is necessary to fulfil other Council Directives (The Urban Waste Water Treatment (England and Wales) Regulations, 1994). WwTWs above 10,000 p.e. that discharge into these sensitive areas are required to remove 80% of the influent phosphorus or achieve a final effluent concentration of 2 mg P/l, while works above 100,000 p.e. must achieve 1 mg P/l in the final effluent. There are currently 588 designated sensitive areas across the UK and 448 WwTWs above 10,000 p.e. that discharge into these areas (Defra, 2012f).

The UWWTD has resulted in a significant increase in the quantity of phosphorus being removed from WwTWs. Reviews of sensitive areas are carried out every 4 years, which could result in additional phosphorus removal requirements if more rivers are designated as sensitive.

4.1.2.2 Water Framework Directive

The Water Framework Directive (WFD) (The European Parliament and the Council of the European Union, 2000) came into force on 22nd December 2000 and was transposed into UK law in 2003 with the publication of The Water Environment (Water Framework Directive) (England and Wales) Regulations (2003). The WFD is designed to enhance the status of aquatic ecosystems and prevent further deterioration, promote sustainable water use and reduce pollution of both surface water and groundwater (Defra, 2012g).

In particular, under the WFD member states must strive to achieve 'good status' for surface and ground water by 2015 (Defra, 2012g), with 'good' ecological status being described as having characteristics that are similar to those expected under nearly undisturbed conditions (Environment Agency, 2009b). For phosphorus, there is no internationally agreed standard for the trophic state of waters at different total phosphorus concentrations (Johnston and Dawson, 2005), but the generally accepted standard for a healthy river in the UK would be to have a background concentration below 0.1 mg P/l (Pratt et al., 2012). A study of the River Frome in the UK confirmed that algal growth is reduced when phosphorus concentrations (measured as Soluble Reactive Phosphorus, SRP) fall below 0.9 mg P/l (Bowes et al., 2011). Pratt et al. (2012) surveyed 98 rivers in the UK, and found that around 80% had phosphorus concentrations exceeding the 0.1 mg P/l target. Overall, it is estimated that 45% of rivers in England and 7% in Wales exceed their phosphorus standard (ESPP, 2013c). Due to the disproportionate cost and uncertainty of achieving the WFD targets, the timescales have been relaxed and the target date has been put back to 2027 (UKWIR, 2010).

The WFD differs from the UWWTD in that it specifies outcomes, such as achieving certain levels of river quality, rather than outputs, such as effluent discharges from WwTWs. This approach allows the use of source apportionment methods to determine the relative contributions of point and diffuse pollution, allowing more cost-effective methods to be developed. White and Hammond (2006) estimate UK agricultural diffuse pollution to be 12.8 kt P/year, while UKWIR (2010) suggest that WwTWs discharge 24.2 kt P/yr to water systems (13.8 kt P/yr to rivers and 10.4 kt P/yr to estuaries). Also, evidence suggests that point sources (such as WwTWs) pose the greater risk of eutrophication in UK rivers due to the form and timing of the phosphorus loading (Jarvie et al., 2006). Therefore, it is likely that the WFD will place an increasing requirement on the water industry to reduce phosphorus discharges from WwTWs.

The WFD also affects the UWWTD. The UWWTD defines a ‘sensitive’ area as one where further treatment is necessary to fulfil other Council Directives, therefore any water that is below a ‘good’ status and receiving wastewater effluent should now be classified as a ‘sensitive’ area under the UWWTD as this discharge requires further treatment to fulfil the council directive. At a minimum, this will result in more WwTWs being designated with 1 or 2 mg P/l discharge consents under the UWWTD. Furthermore, achieving the WFD targets will require enhanced levels of phosphorus removal at certain WwTWs, reaching levels below 1 mg P/l, which will result in additional quantities of phosphorus being removed from wastewater.

No study was identified that estimates how the WFD will affect the mass balance of phosphorus across the whole industry.

4.1.2.3 Climate change targets

It is estimated that the UK water industry currently contributes around 1% to the total greenhouse gas emissions in the UK (End-O-Sludg, 2012). The UK government has set legally binding targets of reducing emissions by 34% by 2020 and 80% by 2050 compared to 1990 levels (Foresight, 2011). Under the Carbon Reduction Commitment (CRC) scheme, the water industry will have to achieve similar GHG emissions reductions (Environment Agency, 2009a). However, energy use in the industry has more than doubled since 1990, which is largely due to the adoption of more energy-intensive processes to meet higher treatment standards (Severn Trent Water, 2010). Energy intensive processes for removing, recovering and recycling phosphorus will make it more difficult for the industry to meet its carbon reduction commitments.

4.1.2.4 EU phosphorus recycling legislation

The European Union has for a long time seen itself as a food secure region, however, Schröder et al. (2010) demonstrate that the EU food system is highly vulnerable to future phosphorus scarcity. This section investigates the movement at the European level towards introducing phosphorus recycling objectives, as well as the initiatives already implemented within some European countries.

The Europe 2020 Strategy sets out the European Commission's vision for the EU in 2020 (EC, 2010b). It contains three priority themes of Smart, Sustainable and Inclusive growth and five specific targets that should be achieved (EC, 2010b). In order to catalyse the progress of each theme, the Strategy also includes seven flagship initiatives. 'Resource Efficient Europe' is a flagship initiative under the ‘Sustainable Growth’ theme and is intended to support the shift towards a low-carbon, resource efficient economy (EC, 2010b).

The Resource Efficient Europe flagship initiative led to the development of the Roadmap to a Resource Efficient Europe (Fischer et al., 2012). The Roadmap highlights the fact that growth in Europe over the last few decades has been based on intensive use of resources (EC, 2011). It also warns that the era of cheap resources is over and that many enterprises and consumers have yet to realise the scale and urgency of the changes that are required (EC, 2011). It suggests that fundamental changes are required to ensure continued growth in the future, and stresses the importance of recycling to improve security of supply (EC, 2011). The Roadmap sets out a vision for 2050, which includes meeting climate change targets and sustainably managing all resources (EC, 2011). This will be achieved through increased resource efficiency and by moving towards a circular economy where all wastes are turned into resources. The Roadmap also includes milestones for 2020, which includes ensuring recycling becomes more economically attractive, developing markets for secondary materials, reducing resource inputs to the food chain by 20%, and halving the amount of edible food waste that is currently disposed of (EC, 2011). The Commission will also assess the introduction of minimum recycling rates for specific materials (EC, 2011). The sustainable supply of phosphorus was highlighted within the Roadmap as an issue for long term global food security. Consequently, the Commission proposed to assess security of supply concerns and potential actions for sustainable use of phosphorus, and publish a Green Paper on Phosphorus by 2012 (EC, 2011).

A Green Paper on Phosphorus would initiate a formal consultation on bringing phosphorus stewardship and recycling into EU policies, and could lead to an EU Phosphorus Directive (ESPP, 2013a). However, the Green Paper, which was proposed for 2012, has not yet been produced. Speaking at the 1st European Sustainable Phosphorus Conference in Brussels on 07 March 2013, Janez Potočnik, the European Commissioner for Environment, mentioned the difficulties of attempting to tackle longer-term environmental issues during times of economic hardship (Potočnik, 2013). Potočnik warned that, although supplies of phosphorus are likely to last many years and the EU has good trading relations with producing countries, the EU is vulnerable to price volatility and geopolitics and cannot afford to wait to deal with the problem (Potočnik, 2013). Potočnik hoped to be able to present the Green Paper on phosphorus in the coming months (Potočnik, 2013), although this remains unpublished as of July 2014.

The European Commission has, however, launched a public consultation on the Sustainability of the Food System, which was open from July 2013 to October 2013, and was designed to explore how it can move towards a more sustainable and resource efficient food system (EC, 2013a). The consultation gathered inputs around the areas of technical knowledge, promoting and stimulating sustainability, reducing food waste, and improving policy coherence (EC, 2013b). Over 600 responses were received from all EU member states and many other countries, and the results from this consultation, along with a Communication on the Sustainability of the Food System are due to be published in 2013/14 (EC, 2013b). As of July 2014, no results have yet to be published.

4.1.3 Phosphorus removal

In order for phosphorus to be recycled from wastewater, it must first be removed and prevented from being discharged into rivers and seas. Phosphorus that is discharged into rivers can cause eutrophication, which has a detrimental impact on the aquatic ecosystem (Smith et al., 1999, Millennium Ecosystem Assessment, 2005), and phosphorus has been identified as the principal reason for failure to meet WFD quality objectives for UK inland surface waters (ESPP, 2013c). Therefore, phosphorus removal processes are required at UK WwTWs, driven by environmental legislation. This section considers the phosphorus removal processes currently in place within the UK water industry.

The average influent concentration to a WwTWs in the UK is estimated at 9.1 mg P/l (UKWIR, 2010). At WwTWs without any specific phosphorus removal process, the phosphorus is roughly evenly divided between the sludge and final effluent (Environment Agency, 2012). This suggests that final effluent would contain at least 4.5 mg P/l. Water is also removed within the sludge, which will further increase the phosphorus concentration of the final effluent phosphorus, although no measured average value was identified in the literature.

In order to reach WFD targets of 0.1 mg P/l within rivers, a final effluent from a WwTWs containing 4.5 mg P/l would require considerable dilution from river water, which is often not available, and this water must have a phosphorus concentration below 0.1 mg P/l, which is often not the case due to upstream point and diffuse pollution. Therefore, specific phosphorus removal processes are required, which are generally either chemical or biological. With such processes installed, the amount of phosphorus removed from wastewater can be increased substantially. For example, the removal efficiency from municipal wastewaters in Finland is estimated to be around 95% (Antikainen et al., 2005).

By 2010, 478 WwTWs in the UK operated phosphorus removal processes, and by 2015 this number is expected to increase to 639 works, serving a p.e. of 23 million people (UKWIR, 2010). The level of phosphorus removal required to meet WFD targets will be greater than the strictest consents imposed under the UWWTD (1 mg/l), especially in areas with inadequate dilution, and phosphorus removal will also be required at the smaller WwTWs (<10,000 p.e.) (Bowes et al., 2010). In fact, the Environment Agency (2012) has suggested that an additional 2,000 WwTWs may be contributing to the exceedance of downstream water quality standards and will therefore require phosphorus removal processes.

The increasing demand for phosphorus removal to meet river quality targets presents the opportunity to couple this with increased recovery and recycling from wastewater. However, existing regulations do not specify which method of phosphorus removal should be adopted, and the method can affect the recovery potential (see Section 4.1.5).

4.1.3.1 Chemical phosphorus removal

Chemical phosphorus removal methods were developed in the 1950s and involve the addition of metal salts to the wastewater to form insoluble metal phosphates which can be settled out by sedimentation (Morse et al., 1998). Chemical precipitation is now the most common form of phosphorus removal employed in the UK since it is relatively cheap and easy to retrofit, install and operate (Ofwat, 2005). It is also viewed as more reliable than biological phosphorus removal, and is capable of achieving phosphorus removal to less than 0.5 mg P/l (ACHS, 2009). Assuming an influent concentration of around 9 mg P/l, this is a removal efficiency of greater than 94%.

Achieving a final effluent phosphorus concentration of 1 mg/l at a works with 1 million p.e. using chemical precipitation is estimated to involve a capex cost of around £2m, and opex costs of £0.3m per year (UKWIR, 2010, Environment Agency, 2012).

The most suitable metals for phosphorus removal are iron and aluminium, added as chlorides or sulphates, and lime may also be used (Morse et al., 1998). Fe-based coagulants are more often used for phosphorus removal since they are considered to be cheaper than aluminium salts (Ofwat, 2005) and because the Environment Agency (EA) reluctantly provides discharge permits for Al due to toxicity concerns (Environment Agency, 2012).

The use of chemicals for phosphorus removal also has some disadvantages. The continuous consumption of metals, iron or aluminium, can be viewed as less sustainable than biological methods of removing phosphorus (Hislop and Hill, 2011), and it also raises concerns regarding the future security of supply and price of these metals. The use of chemical precipitants increases sludge production by around 20-30% for aluminium and up to 45% for iron, which raises sludge handling, treatment and disposal costs (Brett et al., 1997), and anaerobic digestion (AD) of sewage sludge is reported to be adversely affected by chemical phosphorus removal (Smith and Carliell-Marquet, 2009). Also, since iron and aluminium precipitates are thought not to release phosphorus during anaerobic digestion (Brett et al., 1997), there is less opportunity to recover phosphorus from P-rich side streams. Finally, despite being used to remove a pollutant, iron and aluminium are also considered as pollutants themselves and have been included in the WFD (Environment Agency, 2012). New and tighter discharge permits for iron and aluminium may necessitate additional costs for tertiary treatment to remove these pollutants, or encourage companies to consider alternatives, such as biological phosphorus removal (Environment Agency, 2012). Due to the issues with chemical precipitation, it has been suggested that the UK water industry is now increasingly favouring biological phosphorus removal methods over chemical precipitation (Gaterell et al., 2000).

4.1.3.2 Biological phosphorus removal

Biological phosphorus removal was developed in the 1960s (Rybicki, 1997) upon recognition that under certain conditions bacteria could be encouraged to take up increased amounts of phosphorus (Morse et al., 1998). In conventional activated sludge (AS) plants, bacteria only use enough phosphorus to satisfy their basic metabolic requirements, resulting in removal rates of 20-40% (Brett et al., 1997). However, under anaerobic and/or anoxic conditions followed by aerobic conditions, certain bacterial strains are capable of removing 80-90% of the phosphorus (Brett et al., 1997). This process is often referred to as enhanced biological phosphorus removal (EBPR) and is now a fully established technology, with around 20 works expected to be employing EBPR in the UK by 2015, serving a population of around 5.2 million people (UKWIR, 2010). Barnard and Steichen (2006) suggest that biological phosphorus removal can be used to achieve average orthophosphate discharges of around 0.1 mg-P/l, and even lower levels (0.03 – 0.07 mg-P/l) can be achieved if chemicals are used in a further ‘polishing’ step.

There are, however, some drawbacks to operating EBPR systems, with the main concerns being the increased costs and reduced reliability. Achieving a final effluent phosphorus concentration of 1 mg/l at a works with 1 million p.e. using EBPR is estimated to involve a capex cost of around £5m, and opex costs of £0.6m per year (UKWIR, 2010, Environment Agency, 2012). This is around twice the cost estimated for chemical precipitation.

Also, achieving reliably low concentrations in the treated wastewater is more difficult with biological methods as factors such as high rainfall and nutrient limitations can cause process upsets, performance deterioration and even failure (ACHS, 2009).

The EBPR process cannot currently be applied to trickling filter systems (Morse et al., 1998), but instead requires an AS process, and therefore is not applicable for the majority of WwTWs in the UK without a process upgrade or rebuild (ACHS, 2009). However, where AS plants are already in operation, such as at many of the larger works, the modification is relatively inexpensive (ACHS, 2009) and there are operational savings associated with the reduced consumption of chemicals and the reduced production of sewage sludge.

Another issue with the EBPR systems is that if the bacteria are placed under anaerobic conditions again, such as during anaerobic digestion, the phosphorus can be re-released, moving into digestate liquors which are returned to the head of the works. A mass balance conducted at Thames Water's Slough STW showed that the return liquors were contributing around 26% of the total load to the works (Jaffer et al., 2002). High concentrations of phosphorus in these liquors can lead to the problematic formation of struvite within pipes, pumps and centrifuges, and requiring substantial amounts of resources to rectify (Petzet and Cornel, 2012). However, these P-rich side streams, which do not exist with chemical phosphorus removal methods, create the potential to recover phosphorus, often as struvite or calcium phosphate.

4.1.3.3 Other methods of phosphorus removal

Additional methods of phosphorus removal may be required to reduce effluent phosphorus concentrations and meet WFD river quality targets. Such methods include filtration, adsorption, ion exchange and electrodialysis. However, achieving higher levels of phosphorus removal will incur additional costs. For example, it is estimated that the costs for phosphorus removal increase rapidly below 1 mg P/l, reaching double the cost to achieve a 0.1 mg P/l final effluent (Environment Agency, 2012). However, the literature review revealed no WwTWs in the UK that were operating at this level of phosphorus removal.

4.1.4 Sewage sludge

The material that is removed from wastewater, which includes phosphorus, ends up in the sewage sludge. This section considers how the water industry currently manages sewage sludge, including the current disposal routes, and the regulations and challenges associated with this disposal.

Data submitted for the 2010 June Return reported that English and Welsh water companies produced over 1.3 million tonnes dry solids within sewage sludge (Environment Agency, 2010). UKWIR (2010) estimate that 50% of the influent phosphorus is removed from the wastewater into the sewage sludge, which contains 24.2 kt P/yr. Increasing the level of phosphorus removal to meet water quality targets will increase the amount of phosphorus found within sewage sludge.

This sewage sludge needs to be removed from the WwTWs. It is also potentially valuable since it contains plant nutrients and organic matter. The UWWTD has banned sewage sludge disposal to the seas (Defra, 2002), and the EU Landfill Directive is making it increasingly expensive to dispose of sewage sludge to landfill (Defra, 2009b, Defra, 2011d). The remaining options for sewage sludge disposal are either use on agricultural or non-agricultural land, or incineration. It is estimated that, in 2009/10, 71% of sludge was sent for recycling (including use in agriculture, land reclamation, composting, and others), 18% was sent for thermal destruction (including incineration, and co-firing with other fuels), while just 0.6% of sewage sludge was sent to landfill (Water UK, 2010).

4.1.4.1 Recycling to agricultural land

UKWIR (2010) estimate that sewage sludge contains 24.2 kt P/yr, of which 71% was recycled to agricultural land or similar (Water UK, 2010), which suggests total recycling of 17.2 kt P/yr. The direct application of sewage sludge, or biosolids, to agricultural land represents a cost-effective method of recycling nutrients, including phosphorus, back to agriculture (ACHS, 2009) and is considered the Best Practicable Environmental Option (BPEO) by the UK Government (Water UK, 2006a). As well as providing macro- and micro-nutrients to plants, the sewage sludge also provides organic matter which helps to improve the structure, drainage and water retaining capacity of the soil (Water UK, 2006a).

However, sewage sludge can contain pathogens, heavy metals, organic compounds and pharmaceuticals which are potentially harmful to human health and the environment. Therefore, the practice of recycling sewage sludge to agriculture is highly regulated under EU Sewage Sludge Directive (86/278/EEC) (The Council of the European Communities, 1986), the Sludge (Use in Agriculture) Regulations (1989), the Code of Practice for Agriculture Use of Sewage Sludge (DoE, 2006) and the Safe Sludge Matrix (ADAS, 2001). Under these regulations and other best practice guidelines, recycling sewage sludge to agriculture is common practice in the UK. The European Commission is currently assessing whether the Sewage Sludge Directive should be reviewed, which could include stricter limits for 'classical' inorganic and organic contaminants such as heavy metals, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), as well as emerging compounds such as pharmaceuticals, flame retardants and personal care products (EC, 2012).

In addition to complying with the sludge recycling legislation, there are some significant challenges associated with recycling sewage sludge to agriculture. One of which is that sewage sludge is a bulky material and incurs high transportation costs, therefore most recycling occurs within 25km of the WwTWs generating the sewage sludge (UKWIR, 2010). This limits the area of land available for sludge applications, especially where urban WwTWs are generating large volumes of sludge but have limited available surrounding agricultural land. The Nitrates Directive (91/676/EEC) places further restrictions on the amount of sewage sludge that can be recycled to agricultural land within nitrate vulnerable zones (NVZs) (The Council of the European Communities, 1991a). A number of processes including drying and granulation are now being, or have been, developed to allow sewage sludge to be transported over larger distances and increase the area of land available for sewage sludge recycling.

Due to the imbalance of nutrients within sewage sludge, applying sewage sludge up to nitrogen limits often results in an over application of phosphorus, above crop requirements. Depending on the type of biosolid being applied, applications at a rate of 250 kg/ha total N would supply 200-400 kg/ha phosphate (P_2O_5), which lead to an increase in soil phosphorus status (ADAS, 2013). The Sludge (Use in Agriculture) Regulations (1989) states that sludge applications should take into account the nutrient needs of the plants, whilst not impairing the quality of the soil and surface and groundwater. However, the Regulations do not specify application limits based on the phosphorus content of the sewage sludge or the soil, as is the case for heavy metals concentration. The Biosolids Nutrient Management Matrix, which came into effect from 01 January 2014, was designed to address this issue by imposing a simple, self-limiting system where biosolids applications are restricted based on the soil phosphorus content (or P-index), the type of soil and the type of biosolid (ADAS, 2013). As the soil P-index increases, biosolids applications become restricted. For example, applications of lime-stabilised biosolids to sandy soils at P-index 3 are only allowed for 1 year in 4, and no biosolids application is permitted for soils at P-index 5. The Biosolids Nutrient Management Matrix is said to be “consistent with the good practice advice in [the Fertiliser Manual] RB209” (ADAS, 2013). This restriction of applications based on the P-index of receiving soils is likely to further reduce the land available for recycling biosolids.

Another concern is the plant availability of the phosphorus within sewage sludge, which is affected by the method of phosphorus removal. Elliott and O’Connor (2007) compared phosphorus availability to Triple Superphosphate (TSP), a common mineral fertiliser, and found that works using EBPR were most available (>75% of TSP), whereas sludges from works using chemical precipitation were considerably less available (<25% of TSP). Within the Fertiliser Manual (RB209) it estimates that the phosphorus availability in digested cake, thermally dried, lime stabilised and composted sewage sludge is 50% (Defra, 2010d).

4.1.4.2 Thermal destruction

Thermal destruction methods, primarily incineration but also other methods such as pyrolysis, gasification, and super-critical water oxidation (SCWO), are increasingly being employed to process sludge where recycling to land is not a feasible option. Approximately 18% of sewage sludge was sent for thermal destruction in 2009 (Water UK, 2010).

Incineration completely destroys organic contaminants and pathogens which may remain in the sewage sludge (Petzet and Cornel, 2011), although the ashes then contain increased concentrations of heavy metals and the phosphorus is poorly available for plants, so further treatment is necessary (Hermann, 2009). The nitrogen within sewage sludge is also lost during incineration.

Only three companies in England and Wales (Thames Water, United Utilities and Yorkshire Water) currently incinerate sludge, and of this Thames Water incinerated 57.5% of the total amount of sludge. With increasing restrictions applied to recycling sewage sludge to agricultural land, it is anticipated that incineration capacity will be increased in the UK. For example, United Utilities, one of the largest UK water and wastewater companies, intends to reduce its reliance on sewage sludge disposal to agriculture from 80% to 50% by increasing incineration capacity (Barber, 2009), and Northern Ireland Water has increased incineration capacity to treat 100% of its sewage sludge (NI Water, 2014).

There are now several methods for recovering phosphorus from incineration ashes which are discussed further in Section 4.1.5, although no full-scale applications of phosphorus recovery from incineration ashes were identified in the UK.

4.1.5 Phosphorus recovery

Phosphorus recovery is defined within this thesis as a process that is specifically designed to extract valuable fertiliser products from wastewater, sewage sludge or incineration ash. Phosphorus recovery from wastewater is normally associated with phosphate crystallisation techniques that can usually form a useful end product (Brett et al., 1997). This differs from phosphorus removal, which is designed to remove phosphorus from wastewater to meet discharge consents and protect water bodies, and generally moves phosphorus from wastewater into sewage sludge which is then disposed of. This section presents an overview of phosphorus recovery technologies that have been, or are currently being developed, and those that are now operating in the UK. The goal is to identify specific technologies that could be adopted by the UK water industry to increase phosphorus recycling from wastewater.

Phosphorus recovery can occur at several locations within a wastewater treatment plant, as shown in Figure 3. These ‘hot spots’ for phosphorus recovery include recovery from the aqueous phases (undrained sewage sludge and sludge liquors after dewatering), treatment and recovery from incineration ashes, and the direct application of sewage sludge to agricultural land. Other locations within a WwTWs include side streams, such as the return activated sludge, or additional processing of dried sewage sludge.

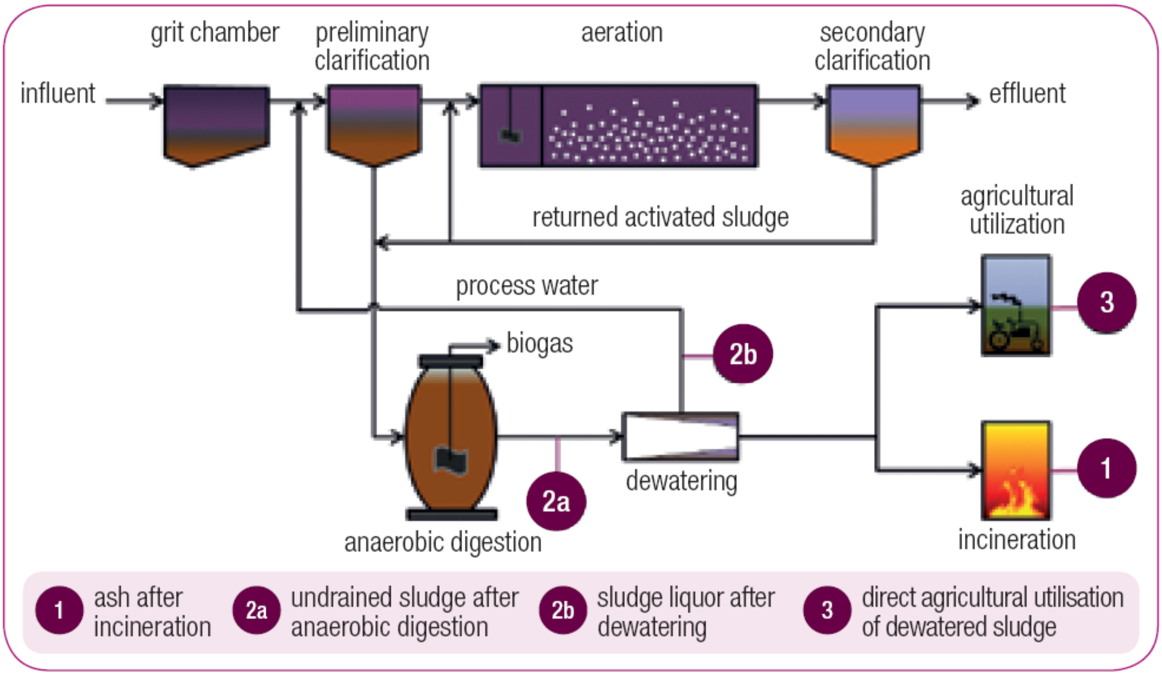


Figure 3: Potential locations for phosphorus recovery from wastewater.

Source: Kabbe (2013)

The two most common products associated with phosphate recovery through precipitation are calcium phosphate and struvite. Calcium phosphate ($Ca(PO_4)_2$), also referred to as CaP or HAP (hydroxyapatite), is essentially the same material as that derived from phosphate rock. It is therefore unsuitable for direct application due to low bioavailability, but can be processed into phosphate fertilisers (Adam, 2009b). At the First International Conference on Phosphorus Recovery and Recycling in 1998, it was believed that recovering calcium phosphate from wastewaters would be the predominate route for phosphorus recovery, providing the phosphate industry with a significant proportion of its raw material needs (Driver, 2004). However, this has not materialised and instead struvite recovery is now seen as the more feasible route for phosphorus recovery (Driver, 2004).

Magnesium ammonium phosphate hexahydrate ($MgNH_4.PO_4..6H_2O$), or struvite, is composed of equal parts of magnesium, ammonium and phosphate. Struvite has been demonstrated as a suitable slow-release fertiliser and is considered to be the most promising form of phosphorus that can be recovered from WwTWs (ACHS, 2009). Struvite is sometimes referred to as MAP, but as this acronym is also used for a mineral fertiliser (mono-ammonium phosphate), this will be avoided in this thesis.

Struvite can be formed by adding magnesium ions (normally as magnesium oxide (MgO) or magnesium chloride ($MgCl_2$)) to streams containing high concentrations of phosphate and ammonium ions (Parsons, 2001). Since struvite solubility decreases as pH increases, it is possible to increase recovery rates by increasing the pH, either by adding an alkali, such as sodium hydroxide ($NaOH$), or degassing the solution to remove CO_2 (Parsons, 2001).

Controlled struvite recovery has several benefits. The first, and perhaps most important, benefit is reducing ‘wild’ struvite formation in pipes and pumps, which reduces maintenance costs. For example, a struvite recovery facility installed at Slough WwTWs is expected to save around £200,000 per year on chemical costs required to clear pipes of struvite (BBC News, 2013). Also, when phosphorus is removed before dewatering sewage sludge, it increases the dewaterability of this sludge, which reduced sludge transportation costs. Another benefit is gained by reducing the phosphorus content of sewage sludge, which facilitates recycling to agricultural land by reducing the over application of phosphorus and resulting build-up of phosphorus within the surrounding soils. Finally, removing N and phosphorus from return streams reduces the overall N and phosphorus load to WwTWs and therefore reduces the overall treatment costs. For example, as mentioned in Section 4.1.3.2, the return liquors at Slough WwTWs were estimated to contribute 26% of the total phosphorus load to the works (Jaffer et al., 2002).

Certain conditions are required for effective phosphorus recovery. In general, a high concentration of soluble phosphorus is required, at least 75 mg P/l (Environment Agency, 2012). This can be compared to the average influent phosphorus concentration of UK wastewaters, which are estimated at around 9.1 mg P/l (UKWIR, 2010). Phosphorus removal methods increase the concentration of phosphorus in side streams, although the use of chemicals such as iron or aluminium for phosphorus removal produces a low concentration of soluble phosphorus, so recovery is largely only feasible from side-streams at treatment works employing EBPR processes (Environment Agency, 2012). The size of phosphorus load is also an important factor in determining the economic feasibility of a phosphorus recovery plant. For example, according to Britton (2009), the Ostara Pearl process requires a WwTWs >20 million litres per day, which, assuming that each person uses 150 l/day (Water UK, 2006b), translates into works >130,000 p.e.

A mass balance across Thames Water's Slough WwTWs, found that the most suitable side-stream was the centrifuge liquors, since phosphorus is released from EBPR sludge during anaerobic digestion (Jaffer et al., 2002). Other processes are available to release phosphorus from EBPR sludges and produce a stream of concentrated soluble phosphate. For example, the Phostrip process uses a 'stripper' tank to hold return activated sludge under anaerobic conditions to release the phosphorus (Kaschka and Weyrer, 1999), while the Wasstrip process involves adding volatile fatty acids (VFAs) to waste activated sludge (WAS) to release phosphorus (Environment Agency, 2012). The Heatphos process involves heating sludge from EBPR for an hour at 70^{o}C to release the phosphorus (Kuroda et al., 2002), and the Prisa process combines supernatant from pre-thickened, acidified sludge prior to AD, with supernatants from post-thickeners and belt presses to produce an optimised blend of soluble nutrients (Montag et al., n.y.).

With a concentrated stream of soluble phosphorus, controlled phosphate precipitation can occur using various processes. Some processes involve the use of reactors that have been developed to encourage crystallisation and produce pellets that can be used as a granular fertiliser. The reactors consist of fixed beds (e.g. Kurita Fixed Bed Crystallisation column), fluidised beds (e.g. Ostara's Pearl Reactor (Britton, 2009), DHV Crystalactor (Giesen, 2009), P-Roc (Kalogo and Monteith, 2008) and Prophos processes (BMBF/BMU, 2013)), and also aerated columns (e.g. Phospaq (Paques, 2013), Unitika Phosnix (Morse et al., 1998), Airprex (SH+E Group, 2012), Buddenheim (CEEP, 2013) and NuReSys processes (NuReSys, 2013)). Under optimum conditions, some of these processes are capable of removing >90% of the phosphorus as struvite from concentrated side streams, and several processes are now operating at demonstration and full-scale installations.

A criticism of phosphorus recovery from the liquid phase is that the amount of recoverable phosphorus is relatively small. Petzet and Cornel (2011) suggest that only around 40% of the total inflow to a works is recoverable from the liquid phase, and then only if the works has EBPR. A report by UK Water Industry Research (UKWIR) concluded that even if all UK

WwTWs >200,000 p.e. were converted to EBPR, the amount of phosphorus recoverable as struvite would be in the region of 1.4 kt P/yr, which is less than 1% of the annual requirement for fertilisers by UK agriculture (UKWIR, 2010).

Phosphorus can also be recovered from incineration ashes, or the ashes of other thermal destruction processes. It is estimated that around 18% of the sewage sludge produced by UK WwTWs in 2009/10 was sent for thermal destruction (Water UK, 2010). Recovery from incineration ashes typically involves leaching with acids or alkalis to solubilise the phosphorus from the ashes, and then subsequent processes to recover the phosphorus, often separating heavy metals at the same time. The advantage of phosphorus recovery from incineration ashes is that the ashes contain much more of the total phosphorus load to the works (around 90%) compared to recovery from the aqueous phase, which contains only around 40% of the phosphorus (Petzet and Cornel, 2011). Also, water companies will typically operate very few incinerators compared to the number of WwTWs, instead transporting sludge to these centralised locations, which significantly reduces the number of phosphorus recovery processes required and may improve the feasibility of such processes. The new sludge strategy of Canton Zurich, Switzerland, has the condition that either the phosphorus is recovered from the incineration ashes, or the ash is stored in a way that will enable phosphorus to be recovered in the future (ESPP, 2013b). Also, in Sweden, authorisation to construct a new sludge incinerator is permitted with the condition that phosphorus must be recovered (Hultman, 2001).

A combined solution of enhanced phosphorus removal, phosphorus recovery from the aqueous phase, and recycling of sewage sludge or phosphorus recovery from incineration ashes would enable most of the phosphorus within wastewater to be recovered and recycled. Table 3 lists the main phosphorus recovery processes that have been, or are currently being developed, for phosphorus recovery from wastewater.

Table 3: Phosphorus recovery technologies

Process Name	Process Description	Current scale	Recovered Product	Process requirements
Liquid Faction (side or return streams)				
Ostara's PEARL Process.	The Ostara Pearl Process uses a fluidised bed reactor to produce struvite pellets or 'prills' from nutrient-rich feed streams such as digested sludge supernatant (Ostara, 2012). The feed streams are mixed with magnesium chloride and, if necessary for pH correction, sodium hydroxide, before being fed into the reactor (Ostara, 2012). Under optimum conditions the process is capable of removing up to 90% of the phosphorus and 40% of the ammonia load (Ostara, 2012). The product, which is marketed as 'Crystal Green', has an NPK formulation of 5:28:0 + 10% Mg and undetectable, or extremely low, levels of heavy metals and pathogens (Crystal Green, 2009). Crystal Green can now be sold in the UK as a high quality fertiliser (Environment Agency, 2012).	Full	Struvite (Crystal Green)	EBPR with minimal chemical P removal (Britton, 2009).
P-ROC	The P-Roc (P-recovery from wastewater by crystallisation of calcium phosphate) process is similar to the Crystalactor process, except that it employs tobermorite as the seeding material, as opposed to sand, to precipitate calcium phosphate (Kalogo and Monteith, 2008). The tobermorite, which is composed of calcium silicate hydrates (CSHs), acts as a crystallisation nucleus and is also able to increase the reactor pH due to its chemical properties, therefore promoting the precipitation of calcium phosphate (Kalogo and Monteith, 2008).	Pilot	Calcium phosphate	High soluble P concentration, therefore EBPR.

Process Name	Process Description	Current scale	Recovered Product	Process requirements
Phostrip	The Phostrip process produces a highly concentrated side-stream from return activated sludge (RAS) from which phosphorus can be recovered as calcium phosphate or struvite. The process involves the use of a “stripper” tank, which holds a portion of the return sludge under anaerobic conditions for up to 20 hours, resulting in a thickening of the sludge and a release of the phosphorus held by the microorganisms (Kaschka and Weyrer, 1999). Dosing acid into the stripper tank increases the amount of phosphorus that is released (Environment Agency, 2012). This produces an overflow from the stripper tank with a high P-concentration from which phosphorus can be recovered. The return sludge then contains bacteria with lower cellular phosphorus content, which improves the efficiency of EBPR. A derivation of the process for treating the stripper overflow from the Phostrip process, was the Crystalactor (Rybicki, 1997).	Full	Struvite or Calcium phosphate	EBPR
Phospaq	The Phospaq process takes place in an aerated reactor where phosphate is removed as struvite through the addition of magnesium oxide at pH 8.2 to 8.3 (Paques, 2013). The struvite granules, move to the bottom of the reactor and are removed using a hydrocyclone, before being transferred to a screw press and container (Paques, 2013). The final product has an average size of 0.7 mm and is ready to use as a fertiliser. The Phospaq process is feasible for loads of approximately 100 kg P/day, at 50 mg P-4-P/l and 200 mg Nh4-N/l, and has a removal efficiency of 70-95% (Paques, 2013). The process has been applied at full scale in Olburgen in the Netherlands since 2006, producing 1.2 tons of struvite per day (Phosphorus-recovery, 2012).	Full	Struvite	EBPR

Process Name	Process Description	Current scale	Recovered Product	Process requirements
Crystalactor	The DHV Crystalactor process involves the use of a fluidised reactor that contains seeding grains, such as sand, to crystallise calcium phosphate (or hydroxyapatite, HAP) from concentrated side streams (Morse et al., 1998). Process conditions are controlled through the addition of caustic soda or milk of lime (Morse et al., 1998). The calcium phosphate is removed as water-free pellets that can be recycled by the fertiliser industry (Morse et al., 1998). This final product is unsuitable for direct land application due to low solubility, and so would need to be further processed, although as a raw material it is purer than the phosphate rock used by the phosphate industry (Brett et al., 1997). Under altered process conditions, the Crystalactor fluidised reactor is also capable of producing struvite (Giesen, 2009).	Full	Calcium phosphate. Can be modified for Struvite.	EBPR
Unitika Phosnix	The Unitika Phosnix Process uses an air-agitated column reactor to produce struvite crystals from wastewater through the addition of magnesium chloride and alkali (Morse et al., 1998). The process is claimed to be capable of removing 88-97% of the P, depending on the prevailing conditions (Brett et al., 1997). Precipitation occurs at ambient temperatures using secondary sewage digester effluent with total phosphorus concentrations of 30-905 mg/l (Environment Agency, 2012). Struvite granules of 0.5-1.0mm are produced which contain only trace amounts of heavy metals and form with a 10-day retention time (Environment Agency, 2012, Nieminen, 2010). The process uses natural drying methods to reduce the water content to less than 10% (Nawa, 2009). There are full-scale plants in operation around the world, with the largest of these being situated in Japan (Parsons et al., 2001), including 500m^3/d reactors at Osaka STW (Brett et al., 1997) and the lake Shinji Eastern Clarification Centre of Shimane Prefecture (SECC), which was established in 1998 (Nieminen, 2010). The recovered product is sold to fertiliser companies for around €250/t (Nieminen, 2010), which covers the operating costs.	Full	Struvite	EBPR

Process Name	Process Description	Current scale	Recovered Product	Process requirements
ProPhos	The ProPhos joint research project is investigating and optimising phosphorus recovery at WwTWs, including recovery of struvite and calcium phosphate from the liquid phase, and phosphorus recovery from sewage sludge and sewage sludge ashes. ProPhos study A2 is investigating the use of calcium silicate hydrates (CSHs) as a seeding material within crystallisation reactors to produce calcium phosphate that can be recycled in the fertiliser industry (BMBF/BMU, 2013).	Lab	Calcium phosphate	EBPR
REM NUT	The REM NUT process was originally developed in the 1980s to remove ammonia as struvite. It was reconfigured in 2001 to focus on P-recovery, producing the so-called 'P-driven' REM NUT process (Liberti et al., 2001). The process uses ion exchange to remove phosphorus and ammonia from tertiary wastewater (Brett et al., 1997). In particular, the process involves two ion exchange units, a cationic unit based on natural zeolite to remove ammonium, and an anionic unit which uses a strong base resin to remove phosphate (Liberti et al., 2001). Nutrient removal above 90% is possible (Liberti et al., 2001). Regeneration of the ion exchangers, preferably using sea water, produces concentrated phosphate and ammonium streams which are raised to pH 9.5 and mixed with magnesium to precipitate struvite (Liberti et al., 2001). The struvite is collected in filter bags (Brett et al., 1997), and has an estimated value of €500/t (Liberti et al., 2001). The main drawback of the process are the relatively high costs, both capital and operational and maintenance costs, and in particular the chemical costs for resin regeneration (Liberti et al., 2001). The process has undergone extensive laboratory and pilot scale testing, and two fully-automated 240m^3/d demonstration plants were constructed in West Bari, Italy, in 1983 and South Lyon, USA, in 1986 (Liberti et al., 2001). However, the process has not yet reached full-scale operation due to technical and economic inefficiencies (Petruzzelli et al., 2004).	Demonstration	Struvite	Removes P from tertiary wastewater.

Process Name	Process Description	Current scale	Recovered Product	Process requirements
Kurita Fixed Bed Crystallisation Column	The Kurita Fixed Bed Crystallisation Column is a reactor design that utilises phosphate rock as a seed material to remove phosphorus from secondary effluent through additions of calcium chloride and caustic soda, producing hydroxyapatite (HAP) without any additional sludge production (Brett et al., 1997, Morse et al., 1998). The process conditions can also be altered to produce struvite (Environment Agency, 2012). Full-scale plants are operating in Japan using a modified process similar to the Crystalactor (Environment Agency, 2012).	Full	HAP or struvite	Removes P from secondary effluent. EBPR.
Sewage Sludge (before dewatering)				
AirPrex	The AirPrex process involves treating digested sludge, before dewatering, in an air stripping reactor, which removes CO_2 and increases the pH, therefore promoting struvite precipitation when a magnesium product is added (SH+E Group, 2012). The precipitated struvite forms within the sludge and is either discharged with the solids during sludge dewatering or can be recovered as a fertiliser before the dewatering system through a system of rinsing and drying (SH+E Group, 2012). The struvite product can achieve 80 to 90% purity, with heavy metal concentrations below the defined limit values (SH+E Group, 2012). However, as the struvite is formed within the sludge, therefore being embedded within a complex organic sludge matrix, this hampers the struvite recovery potential (Petzet and Cornel, 2012). The AirPrex process has the advantages of avoiding struvite formation problems throughout the entire system, significantly increasing the dewaterability of sludge, reducing the recycle phosphorus load by around 80 to 90%, and recovering a fertiliser product from wastewater (SH+E Group, 2012). At large WwTWs, these cost savings can amount to several hundreds of thousands of Euros each year (Kabbe, 2013).	Full	Struvite	EBPR

Process Name	Process Description	Current scale	Recovered Product	Process requirements
NuReSys	The NuReSys process recovers struvite from wastewater. The process takes place in two steps: first an air stripping reactor is used to bring the wastewater to the ideal conditions for struvite recovery, which includes raising the pH and fine tuning with NaOH (NuReSys, 2013), then a stirred crystallisation reactor is used to add and mix in $MgCl_2$ and form struvite crystals (N 5%, P_2O_5 28%, Mg 10%) (NuReSys, 2013). Up to 85% of the wastewater phosphorus is removed as struvite pellets, which grow to 1-3 mm in diameter, have low heavy metals content and very similar chemical composition independent of the effluent used, and can be safely recycled as a fertiliser (NuReSys, 2013). The process can run as continuous or batch processing, and can be applied to a range of wastewaters, including digestate, which improves dewaterability, increasing the DM content by 2 to 3 percentage points (NuReSys, 2013). The first plant was built in 2006 and there are now several applications of the process (NuReSys, 2013).	Full	Struvite	Return on investment improved at higher PO_4-P concentrations, >40/45 mg/l required. Suggests EBPR.
Fix-Phos	The FIX-Phos (fixation of phosphorus) process involves adding calciumsilicatehydrate (CSH) into anaerobic digesters, in order to recover phosphorus as calcium phosphate and prevent struvite formation occurring in the digesters, sludge liquor pipes and centrifuges (Petzet and Cornel, 2012). Pilot experiments demonstrated that 21% to 31% of the phosphorus in the digested sludge could be recovered through the addition of CSH (Petzet and Cornel, 2012). The AD process was not impaired by the addition of CSH, and reducing the phosphorus content of the digested sludge increases its dewaterability (Petzet and Cornel, 2012). The recovered product can be recycled as a fertiliser, containing around 18% P2O5 and few heavy metals (Petzet and Cornel, 2012).	Pilot Scale	Calcium phosphate	Recovery rates highest from EBPR sludges and inefficient with chemical P-removal sludges (Petzet and Cornel, 2009).

Process Name	Process Description	Current scale	Recovered Product	Process requirements
Seaborne / Gifhorn Process	The first large-scale pilot plant of the Seaborne process was trialled at Gifhorn WwTWs, operating under altered parameters which led to it being known as the Gifhorn process (Müller et al., 2007, Nieminen, 2010). The Seaborne process is a wet chemical process that involves the treatment of digested sludge to remove heavy metals and organic pollutants, and produces struvite and ammonium sulphate for reuse in agriculture. The first process step uses sulphuric acid to reach pH 1.5 and remobilise heavy metals and nutrients (Müller et al., 2007). A centrifuge and filter system are then used to separate the solids, which are dried and incinerated (Müller et al., 2007). The digester gas, which is high in hydrogen sulphide, is used to precipitate the heavy metals (Müller et al., 2007). However, the use of ferric salts for P-removal disrupts the dissolution of heavy metals in this process (Müller et al., 2007). Sodium hydroxide is added to increase the pH, and magnesium oxide is used to produce struvite (Müller et al., 2007). Surplus nitrogen is separated in a stripping plant, producing ammonium sulphate (Müller et al., 2007). The Gifhorn process was operated under altered parameters to address a number of problems encountered during the start up. The changes included operating a higher pH values (pH 4.5-5) to reduce chemical costs (Nieminen, 2010). The seaborne process is not yet feasible, and future plants should be scaled up to twice or three times larger than the Gifhorn process to increase feasibility (Nieminen, 2010).	Full (not yet feasible)	Struvite	The use of iron salts for P removal disrupts the dissolution of heavy metals in this process (Müller et al., 2007). Suggests EBPR required.

Process Name	Process Description	Current scale	Recovered Product	Process requirements
Budenheim process	The Budenheim process uses pressurised carbon dioxide to dissolve phosphate within sewage sludge and then precipitates calcium phosphate separately from heavy metals through a controlled release of pressure (Scope Newsletter, 2013). The process can recover up to 50% of the phosphorus in the first extraction cycle, and is capable of running multiple cycles for increased recovery (Scope Newsletter, 2013). The heating requirements are low, running at temperatures around 20 ^{o}C, and the CO_2 used in the process could be sourced on site from digesters or CHP units, and can be recycled after decompression (Scope Newsletter, 2013). An advantage of this technology is that it can be applied before dewatering, which increases the dewatering efficiency, resulting in significant cost savings (Kabbe, 2013). Also, the process can be applied to all types of sewage sludge, including those that use iron-salts for P-removal (Scope Newsletter, 2013). The process is now operating at the semi-pilot plant scale (Scope Newsletter, 2013).	Pilot	Calcium phosphate	Any sludges, including sludges from iron P-removal.
Phoxnan	The Phoxnan process involves low pressure wet oxidation (LOPROX) of sewage sludge followed by two filtration steps to produce diluted phosphoric acid which can be recovered as a fertiliser. The LOPROX step uses temperatures between 160-220^{O}C, pressures of 12-28 bar and acidic conditions at pH 1.5 to decrease the content of organic components and oxidise organic pollutants (Blöcher et al., 2012). Passing the LOPROX effluent through an ultrafiltration (UF) membrane removes the remaining solids. A nanofiltration (NF) membrane is then used, which retains heavy metals but has a low retention of P, therefore producing a permeate of clean diluted phosphoric acid which can be recovered as a fertiliser (Blöcher et al., 2012).	Lab	Phosphoric acid	Feasible at works employing EBPR or precipitation with alumina salts, but not for works using iron salts (Blöcher et al., 2012).

Process Name	Process Description	Current scale	Recovered Product	Process requirements
Wasstrip	The Waste Activated Sludge Stripping to Remove Internal Phosphorus process (WASSTRIP^{TM}) involves adding volatile fatty acid (VFA) to waste activated sludge (WAS) to release phosphorus and enable struvite formation, therefore reducing struvite precipitation in anaerobic digesters and dewatering equipment (Environment Agency, 2012). The process, which is currently at the pilot scale, is able to reduce the Mg requirement and increase the phosphorus concentration to the struvite recovery system (Environment Agency, 2012).	Pilot	Struvite	EBPR
Prisa	The PRISA process involves acidification of sludge from EBPR prior to AD in order to dissolve the biologically bound phosphates (Montag et al., n.y.). A pre-thickener is used to separate the supernatant, which contains significant quantities of P. The sludge then goes through AD, with post-thickeners and filter presses producing supernatant streams which contains smaller amounts of P, but are rich in ammonia (Montag et al., n.y.). These three side streams are mixed together and filtered to remove solids, before magnesium oxide (MgO) and caustic soda (NaOH) are added to produce struvite, which is removed in a crystallisation reactor (Montag et al., n.y.). A pilot scale process was able to remove more than 90% of the phosphorus from the mix of side streams by operating at pH>9.2 and molar Mg:N:P ratio of 1.5:6:1 (Montag et al., n.y.). This represents around 40% of the works inflow. The struvite produced had the same fertilisation affect as mineral fertilisers, with heavy metals (Pb, Cd, Cr, Cu, Ni, Zn, Hg) concentrations beneath or within the range of those found in mineral fertilisers, and low or undetectable concentrations of organic compounds (Montag et al., n.y.).	Pilot	Struvite	EBPR

Process Name	Process Description	Current scale	Recovered Product	Process requirements
Heatphos	The Heatphos Process involves heating sludge from EBPR plants, resulting in a release of the polyphosphate (PolyP) held within microorganisms, from which phosphorus recovery can occur by precipitating calcium phosphate (Kuroda et al., 2002). Heating the sludge for an hour at 70^{o}C seems to be the optimum solution, releasing around 90% of the sludge polyphosphates into solution (Kuroda et al., 2002). Calcium chloride can be added to precipitate calcium phosphate without the need for pH correction. Hydrolysis of PolyP to inorganic phosphorus (Pi) happens over time, and increased pH is required to precipitate calcium phosphate from solutions containing Pi (Hirota et al., 2010). The calcium phosphate is precipitated as wet pellets, which have a similar phosphorus content to phosphate rock with low metal content, therefore being suitable for fertiliser manufacturing (Kuroda et al., 2002). A pilot plant was constructed at a WwTWs in Kobe City, Japan, with a full scale plant in Fukuyama City removing 90% of influent phosphorus and producing around 10 kg P/day as calcium phosphate (Hirota et al., 2010).	Full	Calcium phosphate	EBPR
Biological processes for phosphorus recovery from iron sludges.	This process uses biological processes to convert iron salts within sewage sludge to iron sulphide, releasing phosphates in a soluble form and allowing P-recovery (Suschka, 2001). The sewage sludge, which contains precipitated iron phosphate from phosphorus removal, is added to a sulphide rich waste water containing high concentrations of sulphides and Sulphur Reduction Bacteria (SRB) which are expected to assist in the production of iron sulphides (Suschka, 2001). Experimental results confirm the feasibility of the process, although additional work is required to reduce retention times (Suschka, 2001).	Lab	Concentrate stream of soluble phosphate for struvite of HAP recovery.	Applied to iron sludges

Process Name	Process Description	Current scale	Recovered Product	Process requirements
Incineration Ash				
Mephrec	The Mephrec (Metallurgical Phosphorus Recovery) process involves smelting and gasification technology to recover phosphorus and energy from sewage sludge, meat & bone meal, or ashes from mono-incineration (Scheidig et al., 2009). The process involves briquetting dried sludge (>20% TS) and ashes, and smelting in a shaft furnace at around 2,000 ^{o}C with dolomite or limestone added for slag formation and coke added as an energy supply (Petzet and Cornel, 2011). The slag that forms contains calcium phosphate, which is tapped at around 1,450 ^{o}C and granulated using water (Petzet and Cornel, 2011). This separates the phosphorus in the mineral slag from the heavy metals which are either in the liquid metal phase (Fe, Cu, Cr, Ni) or the gaseous phase (Zn, Cd, Hg, Pb) (Adam, 2009b). The calcium phosphate granules can be used as a phosphorus fertiliser, with the P_2O_5 content ranging from 4.6% to 12% depending on the components of the briquettes (Scheidig et al., 2009). Gasification of the organic fraction of the sewage sludge generates energy (Petzet and Cornel, 2011).	Pilot	Calcium phosphate	Unknown.
SUSAN / ASH DEC	The SUSAN (Sustainable and Safe Re-use of Municipal Sewage Sludge for Nutrient Recovery) project involves a thermo-chemical treatment of mono-incineration ashes which removes most of the heavy metals and significantly increases the solubility of phosphorus within the final product (Adam, 2009a). Magnesium chloride or calcium chloride is added to the ashes and the mixture is treated in a rotary furnace at temperatures of 850 – 1000^{o}C with retention times below 20 minutes (Adam, 2009a). This results in the formation of volatile heavy metal chlorides which evaporate and leave the system in the exhaust gases, before being removed during flue gas cleaning (Petzet and Cornel, 2011). The removal of heavy metals is dependent on process temperature. At 1000^{o}C, removal rates above 90% were	Full	Calcium phosphate whitlockite or aluminium phosphate	Can be used on all ashes.

	achieved for cadmium, copper, lead and zinc, whilst removal rates above 70% were achieved for molybdenum and tin, and the remaining heavy metal concentrations were low (Adam, 2009a). The process is capable of reducing heavy metal concentrations for all types of incineration ash, regardless of its composition (Petzet and Cornel, 2011). The remaining P-rich granules are enriched with other nutrients, including additional phosphorus if required, and pelletised to produce a consistent granular fertiliser (ASH DEC, 2008). The product is known as PhosKraft, which is an NPK fertiliser (20:8:8) (Hermann, 2009). The treatment also increases the phosphorus availability for plants (Lederer and Rechberger, 2010), increasing the solubility in citric acid from around 30-50% up to 100% (Environment Agency, 2012). The ashes contain around 20% P_2O_5 in bio-available form, mostly as the calcium phosphate whitlockite or aluminium phosphate (Adam, 2009a), and in field trials, the yield of plants fertilised with $MgCl_2$-treated ashes came close to those fertilised with water soluble SSP control fertilisers (Adam, 2009a). A pilot-plant is operated in Leoben, Austria, with a full-scale demonstration plant planned in Germany in 2009 (Environment Agency, 2012).			

Process Name	Process Description	Current scale	Recovered Product	Process requirements
Thermphos	Thermphos International, located in the Netherlands, and is the only elementary phosphorus producer in Western Europe (Schipper, 2001). The Thermphos process produces P_4 from phosphate rock, and is also able to use incineration ashes as a raw material, providing the ash meets certain standards (Schipper et al., 2001). First, phosphate rock is mixed with incineration ashes and granulated and sintered to produce hard pellets of 1 -2 cm, which are mixed with cokes (reducing agent) and pebbles (SiO_2, for slag formation) (Schipper et al., 2001). The mix is fed into an electric resistance furnace and heated to 1500°C, at which temperature phosphate is reduced to P_4 and leaves the furnace as a gas, which is then condensed and recovered (Schipper et al., 2001). The ash used in the process must have a high phosphorus content and low concentrations of certain metals (iron, zinc and copper in particular) (Schipper et al., 2001). Iron present in the phosphate rock/ash mix forms a separate slag, known as ferrophosphorus (75% Fe and 25% P, with small amounts of other metals), which can be used in the steel industry but reduces the amount of P_4 produced (Schipper et al., 2001).Therefore WwTWs adding iron salts for P-removal would produce ashes that are unsuitable for recycling in the Thermphos process, although this can be avoided with separate incineration of iron-poor and iron-rich sludges (Petzet and Cornel, 2011). Conversely, works adding aluminium for phosphorus removal would produce a more desirable raw material for the Thermphos process, since the aluminium compounds can replace SiO2 for slag formation (Schipper et al., 2001). Thermphos initially decided to replace around 17.5 kt P from phosphate rock with recovered material (Schipper et al., 2001), and the company was aiming to become the world's first 'phosphorus-from-waste' producer (Thermphos, 2012), however Thermphos was declared bankrupt on 21 November 2012 (DutchNews, 2012).	Full. Bankrupt.	P_4	Ashes need low content of iron, zinc and copper. Aluminium ashes are preferred.

Process Name	Process Description	Current scale	Recovered Product	Process requirements
SESAL-Phos	The SESAL-Phos (sequential elution of sewage sludge ash for aluminium and phosphorus recovery) process is designed to recover phosphorus from sewage sludge incineration ashes at WwTWs using Al salts for phosphorus removal. The process involves two stages of acid elution to dissolve the calcium phosphates and form alkaline soluble aluminium phosphates, followed by alkali elution using sodium hydroxide and solids-liquid separation to enable extraction of phosphorus and aluminium (Petzet et al., 2011). The initial treatment with acids increases the amount of phosphorus dissolved during subsequent alkaline elution. Calcium chloride is then added to the alkaline leachate to precipitate calcium phosphate, and the aluminium solution could be reused for P-removal. The process, which is still at the laboratory scale, does not require high temperatures or pressures, but is not suitable for WwTWs using Fe salts for phosphorus removal (Petzet et al., 2011). It is estimated that around 60% of the phosphorus could be recovered, and the final product, which is undergoing fertiliser trials, has low metals content but is high in arsenic. (Petzet et al., 2011)	Lab	Calcium phosphate	WwTWs using Al salts. Not suitable for works using Fe salts.
Sephos / Advanced Sephos	The SEPHOS (Sequential Precipitation of Phosphorus) process involves recovering aluminium phosphate from sewage sludge incineration ashes through the use of acids and alkalis (Schaum et al., 2007). Sewage sludge incineration ashes are first eluted with sulphuric acid at pH-values <1.5 to release most of the P, along with a large portion of the heavy metals (Schaum et al., 2007). The solids are then removed, and sodium hydroxide is added to the filtrate to increase the pH to 3.5, which precipitates aluminium phosphate ($AlPO_4$) but leaves copper and zinc in solution (Schaum et al., 2007). Compared to the ash, the phosphorus content of the SEPHOS product is increased from 9.8% to 12%, while the heavy metal content is reduced by about 70% - 90% (Nieminen, 2010). The phosphate-rich, heavy metal depleted precipitant can then be reused in the Thermphos electrochemical process or the Advanced	Lab	Aluminium phosphate (Sephos). Calcium phosphate or struvite (Advanced Sephos).	Dissolved P is reduced in sludges precipitated with Fe, rather than Al (Pettersson et al., 2008).

	SEPHOS process, although direct application to agriculture is not applicable due to the high aluminium content (Nieminen, 2010). The chemical costs required to produce the aluminium phosphate precipitate are estimated at approximately 2-3 times the current price for raw phosphate (Schaum et al., 2007). The process does not yet have full-scale or pilot demonstrations (Environment Agency, 2012), but is considered successful at the laboratory scale (Sartorius et al., 2011). The Advanced SEPHOS process involves further treatment of the SEPHOS product (aluminium phosphate precipitate) to produce a calcium phosphate product and recycled the aluminium in a treatment works (Schaum et al., 2007). Alkaline treatment of the SEPHOS product dissolves both the aluminium and the phosphorus, allowing the phosphorus to be precipitated and recovered as calcium phosphate by adding calcium to the solution, while the aluminium in solution can be recycled to the treatment works as a precipitant for P-removal (Schaum et al., 2007). The feasibility of nanofiltration to separate phosphorus from the solution was confirmed, with advancements in membrane technology opening the possibility of recovering calcium phosphate or struvite from the permeate (Schaum et al., 2007).			

Process Name	Process Description	Current scale	Recovered Product	Process requirements
Bio-Con	The Bio-Con process consists of drying dewatered sewage sludge, followed by incineration and phosphorus recovery from the ashes (Hultman et al., 2001). The recovery step involves acid leaching of phosphorus and an ion exchange process to produce phosphoric acid (Levlin, 2001). After grinding, the ashes are treated with sulphuric acid, which releases the phosphates and most of the metals, except for calcium and lead which form insoluble sulphates (Hultman et al., 2001). The ion exchange process takes place in four columns which remove ferric sulphate, potassium bisulphate, phosphoric acid and other metals (Levlin, 2001). The phosphoric acid can be used for fertiliser production. The Bio-Con process has been tested at pilot scale at Brønderslev WwTWs, Denmark (Nieminen, 2010), but plans for a full-scale operation in Falun, Sweden, were abandoned for unknown reasons (Environment Agency, 2012).	Pilot	Phosphoric acid	The demand for chemicals (acids and bases) can be significantly reduced if the ashes have a lower Fe/P ration (Hultman and Löwén, 2001).
Bioleaching	This biotechnological process involves using bacteria to leach phosphorus from incineration ash (bioleaching) and separating the phosphorus from heavy metals by accumulating the phosphorus within bacteria (bioaccumulation) (Zimmermann and Dott, 2009). The newly developed bacteria involved in bioleaching (*Acidithiobacillus sp*) were able to release 93% of the phosphorus as orthophosphate, although heavy metals were also released (Zimmermann and Dott, 2009). Up to 66% of the released phosphorus could be accumulated as poly-phosphate in the biomass of bacteria (AEDS-population), which can then be separated from the heavy metals (Zimmermann and Dott, 2009). Release of the stored phosphate, through anaerobic dissolution for example, can enable phosphorus recovery through struvite precipitation (Sartorius et al., 2011). The process has operated successfully at the lab-scale (Sartorius et al., 2011).	Lab	Concentrated stream of phosphate for P recovery.	No reported requirements.

Process Name	Process Description	Current scale	Recovered Product	Process requirements
PASH	The PASH (Phosphorus recovery from Ash) process involves recovering calcium phosphate or struvite from incineration ash, through acid leaching and liquid-liquid separation of iron and heavy metals (Nieminen, 2010). After testing various substances, hydrochloric acid was found to give the largest phosphorus dissolution rate (90%) with a HRT of 60 minutes and no heating requirements, although Fe and heavy metals were also dissolved in the process (Montag and Pinnekamp, 2009). Liquid-liquid extraction involving the use of extracting agents (Alamine 336 and tri-butyl-phosphate (TBP)) was able to remove >99% of the Fe and >95% of most other metals, while leaving the phosphorus in solution (Montag and Pinnekamp, 2009). By adding lime or limestone at pH 3.3-3.6, calcium phosphate could be recovered, which contained 16% phosphorus content in DS, demonstrated good plant availability, and contained heavy metal concentrations below the accepted limits in Germany (Montag and Pinnekamp, 2009). Adding magnesium compounds to precipitate struvite is also an option (Nieminen, 2010). A pilot-scale process is in operation in Aachen, Germany (Nieminen, 2010) and is considered successful at the semi-industrial scale (Sartorius et al., 2011).	Pilot	Calcium phosphate, or struvite.	No reported requirements.

4.1.5.1 Phosphorus recovery in the UK water industry

The first and only full-scale phosphorus recovery plant identified within the UK water industry was opened in November 2013 at Thames Water's Slough WwTWs. The Ostara Pearl process installed at Slough WwTWs produces struvite (magnesium ammonium phosphate) granules from the dewatered sludge liquor return stream. The £2m reactor is expected to produce around 150 tonnes of struvite per year, which will be sold to farmers, and Thames water expects to save around £200,000 per year on the cost of chemicals currently required to clear pipes of struvite (BBC News, 2013). Thames Water will pay a monthly fee over a period of 20 years to Ostara, who designed built and financed the new reactor (WMW, 2013).

4.1.6 Phosphorus flows in the UK water industry

This section considers the amount of phosphorus that flows through the water industry's WwTWs in order to determine the potential contribution that the industry could have towards UK phosphorus security.

UKWIR (2010) have estimated the total phosphorus inputs to UK WwTWs (Table 4). The largest phosphorus flows come from the human excreta (urine and faeces), and the total phosphorus input to UK WwTWs is estimated at 48.4 kt P/year.

Table 4: Phosphorus inputs to UK wastewater treatment works.

Data source: UKWIR (2010)

Source of P input to UK WwTWs	P input (kt P/year)
Urine	6.3
Additives	11.9
Faeces	10.1
Tap Water Dosing	4.8
Domestic Laundry Cleaning Product (DLCP)	3.2
Automatic Dishwasher (ADW)	3.6
Pers. Care products.	0.6
Food Scraps	2.0
Town Centre	4.4
Light Industry	0.2
Trader	1.0
Runoff	0.3
Total	**48.4**

UKWIR (2010) estimate that 50% of the influent phosphorus (24.2 kt P/yr) is removed from the wastewater, ending up in the sewage sludge, and the remaining phosphorus (24.2 kt) is discharged to water (13.8 kt P/yr to rivers and 10.4 kt P/yr to estuaries). In 2009/10, approximately 71% of sewage sludge was sent for recycling to agricultural land, land reclamation and composting, while 18% was incinerated and 0.6% was sent to landfill (Water UK, 2010). This equates to 17.2 kt P/yr recycled to agricultural land, 4.4 kt P/yr within incineration ashes, and 1.4 kt P/yr being sent straight to landfill within sewage sludge.

The 150 tonnes of struvite produced each year using the Ostara phosphorus recovery process at Slough WwTWs is marketed as ‘Crystal Green’ and has an NPK formulation of

5:28:0 (Crystal Green, 2009), which is 28% P_2O_5 or 12% P. Therefore, this struvite production contains approximately 0.018 kt P/yr.

These results suggest that phosphorus flows in UK water industry are large. The following section (Section 4.2) considers how these flows compare to other phosphorus flows in the UK.

4.1.7 Knowledge gaps

This section of the literature review revealed that there is very little detailed information about the existing infrastructure of the UK water companies, including the number and size of WwTWs, the treatment type, phosphorus removal and phosphorus flows at these individual works. This information is required to determine the potential for the industry to contribute towards UK phosphorus security, and in particular, the contributions from different water companies and the feasibility of different phosphorus recovery and recycling options at specific WwTWs. This information was gathered from the water companies and is presented in Section 6.1.

This review of phosphorus recovery technologies has revealed that there are now many technologies that are being developed for recovering phosphorus from wastewater, sewage sludge and incineration ashes. Several of these are now proven at full scale, including Ostara's Pearl process, which recovers struvite and has a full-scale installation at Thames Water's Slough WwTWs. However, the review revealed that there is currently no assessment of the potential for adopting certain phosphorus recovery technologies at UK wastewater treatment works. This analysis was conducted as part of this research. The methodology is outlined in Section 5.1, and the results are presented in Section 6.1.5.

The UK water industry is in a dynamic situation. The need to remove more phosphorus from wastewaters to protect water bodies will present challenges to sewage sludge recycling practices, since applications are now restricted based on the phosphorus content of the soil, while at the same time presenting opportunities to recover more phosphorus from wastewater. A dynamic SFA for the industry, or for individual water companies, could be used to reveal the challenges and opportunities of future phosphorus management. This is included as a recommendation for further research in Section 9.1.

4.2 Quantifying phosphorus flows in the UK

Guiding question: How much phosphorus is found within wastewater and how does this compare to phosphorus flows in other wastes in the UK?

The previous section of the literature review revealed how much phosphorus flows through UK wastewater treatment works. The purpose of this section is to evaluate how the quantity of phosphorus within wastewater compares to other wastes in the UK. This supports the overall aim of the thesis by revealing if the water industry is a key stakeholder in UK phosphorus management, and therefore if the industry would be required to increase phosphorus recycling in the future to address resource security. An analysis of phosphorus flows throughout the UK system will also reveal how dependent the UK currently is on imported sources, and is required to determine how much phosphorus recycling in the UK water industry could contribute towards phosphorus security.

A material flow analysis (MFA) quantifies the flows and stocks of a material-based system, and is considered an indispensable first step towards managing a resource (Graedel and Allenby, 2010). The MFA identifies and tracks the major flows within a system, reveals the main processes in the material's lifecycle, highlights the main stocks where the material is accumulating, and exposes the major losses to the environment or to final sinks where recovery could take place (Brunner and Rechberger, 2004). The MFA was also mentioned within Defra's Resource Security Action Plan as a tool that would assist in the understanding of opportunities for recovery and the value of materials lost from the system (Defra, 2012e).

The underlying principle of a MFA is the conservation of mass, where all flows into a system must be equal to the flows accumulating or flowing out of that system (Graedel and Allenby, 2010). When focussing on an element, such as phosphorus, this analysis is known as a Substance Flow Analysis (SFA) since it is the element that is being considered and not the chemical form within which it may exist (Graedel and Allenby, 2010).

4.2.1 National-scale substance flow analyses for phosphorus

Several SFAs for phosphorus have been conducted at the global scale (Smil, 2000, Liu et al., 2008, Cordell et al., 2009a, Sutton et al., 2013, Smit et al., 2009, Van Vuuren et al., 2010). These estimate that the overall food chain efficiency, moving phosphorus from mined phosphate rock to human consumption, is around 12-20% (Sutton et al., 2013). Several other studies have narrowed down the system boundaries, focussing on the continental scale, such as Europe (Richards and Dawson, 2008, Ott and Rechberger, 2012) and Africa (Cordell et al., 2009a). There are now also an increasing number of SFAs conducted at the country-scale. Table 5 presents a list of all of country-scale SFA studies that were identified in the literature. No complete study was identified for the UK, which represents a significant knowledge gap. Therefore, this analysis will be completed as part of this PhD research.

Table 5: Country-scale substance flow analyses of phosphorus

Author	Country
Antikainen et al. (2005)	Finland
Binder et al. (2009)	Switzerland
Chen et al. (2008)	China
Cordell and White (2010)	Australia
Matsubae-Yokoyama et al. (2009)	Japan
Senthilkumar et al. (2012)	France
Seyhan (2009)	Austria
Seyhan (2009)	Turkey
Smit et al. (2010)	Netherlands
Suh and Yee (2011)	USA

The methods used for developing a country-scale SFA for phosphorus may be similar and useful for analysing phosphorus flows through the UK. Therefore, this section includes a critical evaluation of these methods to inform the development of the SFA for phosphorus in the UK.

4.2.1.1 Defining the boundaries

The first step in producing a SFA is to define the system boundaries, which includes geographical and temporal boundaries. For country-scale SFAs, the geographical boundary is normally the borders of that country. In general, it is estimated that agriculture accounts for more than 90% of all phosphorus applications (Brunner, 2010), therefore, most SFAs of phosphorus are focussed on phosphorus flows through the food production and consumption system. However, some phosphorus flows which are not originally part of this system, such as phosphorus within washing detergents that are discharged to sewers, later join the food production and treatment system and are counted in the analysis.

The temporal boundary has more options. Most SFA studies identified are based on a static model, which presents data from the previous years. A dynamic SFA model involves forecasting future phosphorus flows based on probabilistic trends such as soil phosphorus stocks, crop yields, population growth, and phosphorus recycling scenarios. A dynamic model was proposed by Dumas et al. (2011), which considered how to integrate natural processes, such as movement and availability of phosphorus within soil, with human-managed flows, such as phosphorus inputs through fertilisers and recycling wastes. However, a lack of data was identified as a key difficulty, and no complete dynamic, country-scale SFA models for phosphorus were identified in the literature. Virtually all of the static country-scale SFAs identified in the literature presented phosphorus flows per year. As shown in Table 6, many of these collected data from one year, while other studies involved gathering data from a range of years and presenting an average value. The advantages of gathering data over several years are that annual variations can be averaged out and changes can be monitored over time. The disadvantages are that increasing trends may also be averaged out, and this method involves a significant increase in data gathering compared to an analysis focussing on a single year.

Table 6: The year of study and units of weight used in national-scale substance flow analyses.

Author	Country	Year(s) of study	Unit used for quantities of phosphorus
Antikainen et al. (2005)	Finland	1995 - 1999	t
Binder et al. (2009)	Switzerland	2006	t
Chen et al. (2008)	China	2004	Gg
Cordell et al. (2013)	Australia	2007	kt
Matsubae-Yokoyama et al. (2009)	Japan	2002	kt
Senthilkumar et al. (2012)	France	2002 - 2006	kt
Seyhan (2009)	Austria	2001	g P/capita
Seyhan (2009)	Turkey	2001	g P/capita
Smit et al. (2010)	Netherlands	2005	Gg
Suh and Yee (2011)	USA	2007	kt

4.2.1.2 Quantities of phosphorus

A SFA studies the movement and accumulations of the element. Therefore, all flows are presented as a weight of the element per unit time, and stocks presented as a total weight. However, the units of weight that are used are different. As demonstrated in Table 6, some studies presented the weight as tonnes of phosphorus (t P), while other use thousand tonnes of phosphorus (kt P), or even gigagrams of phosphorus (Gg P). Seyhan (2009) uses g P/capita to enable a direct comparison between two countries, Turkey and Austria.

4.2.1.3 Presenting the information

The SFA produces a large amount of data points for different phosphorus flows and stocks. Presenting this data in a coherent manner can be challenging. It is apparent that although presenting very similar information, a different approach to presentation has been taken in virtually all national-scale SFA studies. However, there are some similarities. In general, most of the SFA studies attempt to present the information in a single figure, although some studies also include separate figures for different sub-systems (Matsubae-Yokoyama et al., 2009, Seyhan, 2009). Arrows are generally used to represent the main flows between processes, which are displayed as boxes. The information displayed on the figures varies. For instance, Senthilkumar et al. (2012) assigns each flow a number, with a key beneath detailing the name of the flow, whereas Smit et al. (2010) labels the flow names on the diagram, and Antikainen et al. (2005) uses a separate figure altogether to name each flow.

To simplify the diagrams, many of the flows are grouped, such as all different fertiliser types are grouped into a single 'fertiliser' flow, and all crop outputs from agricultural land grouped into a single ‘crops’ flow. Many of the figures make use of ‘Sankey’ flows, where the size of the arrow increases relative to the size of the flow, which enables an easy identification of the most significant flows.

There are several different pieces of software available that can be used to balance and present the SFA model. For example, Smit (2010) used STAN, Liu et al. (2008) used PHOSFLOW, and Villalba et al. (2008) used CONSEQUENCE.

4.2.1.4 Approach to uncertainty

Uncertainty is an inherent aspect of the SFA. Antikainen et al. (2005), Binder et al. (2009) and Seyhan (2009) all include uncertainty estimates as a range of results. For example, Antikainen et al. (2005) present a table of maximum, minimum and average values for each data point such as manure to fields, while Seyhan (2009) presents results within the main figures as either single values, or as a range of values such as 100-150 or 100 +/- 50. However, most other SFAs identified did not include such ranges of uncertainty.

There are several methods which can be used to avoid errors and reduce uncertainty. The cross-checking method involves getting two or more estimates for the same data point, and checking that the results are consistent. This removes potential errors and improves confidence in the final result. Senthilkumar et al. (2012) were able to cross-check some of their result using alternative calculations, for example comparing the fodder production to the fodder requirement. Results of the same order of magnitude were considered to confirm the accuracy of the calculations.

If two or more estimates are generated for each data point, a statistical method can be used to calculate the spread of these results. This method is calculating the standard deviation. Two standard deviations correspond to 95% confidence limits that the true value lies within that range. This method was used by Seyhan (2009) to produce an uncertainty range. However, such statistical methods are designed for large data sets which are normally distributed, and therefore less suited to the small number of data points obtained in SFA studies.

An alternative method of producing a confidence range for SFA studies was developed by Hedbrant and Sörme (2001), and is referred to as the HS model. This method involves assigning uncertainty levels to various data sources, such as official statistics or values from literature, and applying an interval to each level. For example, Level 1 data sources may have an interval of */1.1 which means the data is multiplied or divided by 1.1 to achieve a range of results. The intervals are developed through user experience and the range produced corresponds to 95% confidence limits, which is the same as that produced using two standard deviations. The methodology and equations used for developing the uncertainty intervals is outlined in Antikainen et al. (2005). Studies employing the HS model, such as Danius (2002), Antikainen et al. (2005) and Asmala and Saikku (2010), often adapt the number of levels and the factors applied at each level based on user experience.

4.2.2 Sub-system scale substance flow analyses for phosphorus in the UK

Although no complete SFA for phosphorus in the UK was found in the literature, several SFA studies were identified for UK sub-systems, such as the agricultural and wastewater sub-systems. This section presents the information of phosphorus flows in the UK, which will be useful to develop a complete SFA for phosphorus in the UK.

4.2.2.1 Agriculture

Withers et al. (2001) calculated phosphorus imports, exports and internal recycling loops for UK agriculture in 1993. The key results are presented in Figure 4. The results show that fertiliser inputs to agricultural land contained 171 kt P, while animal manure was the largest source of phosphorus input to agricultural land, estimated at 213 kt P. In comparison, sewage sludge inputs were relatively small, containing just 7 kt P. These results are indicative of the current situation, although the size of the inputs, as well as the relative inputs may have changed considerably since 1993.

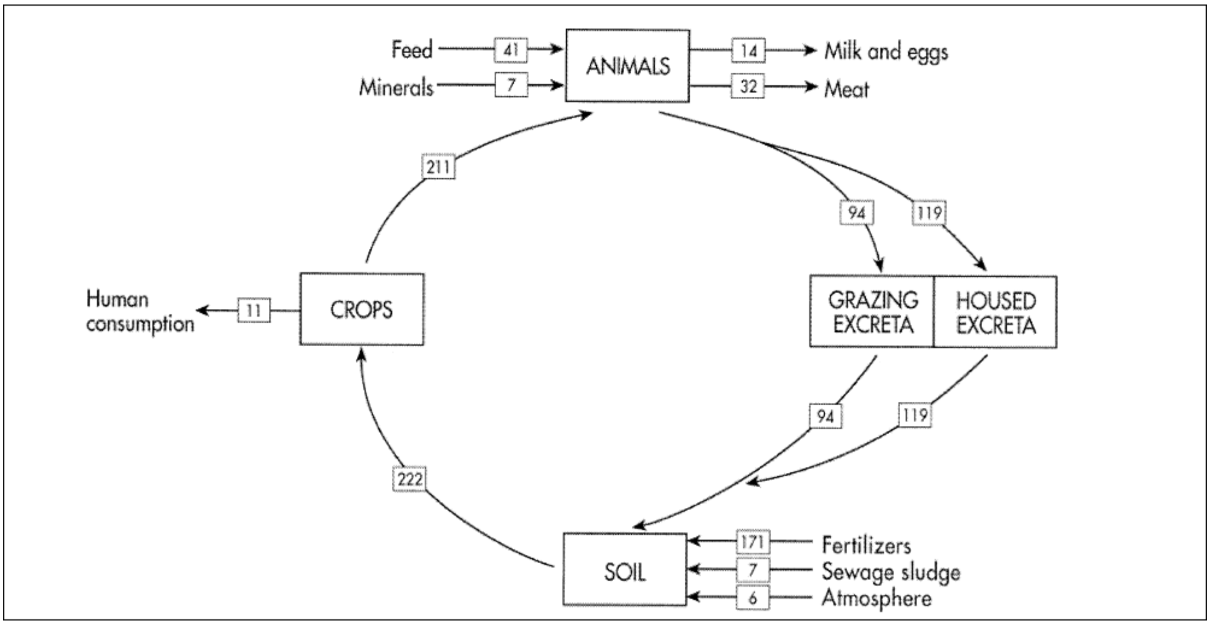


Figure 4: Phosphorus cycling in UK agriculture in 1993.

Source: Withers et al. (2001). Note: Results are in ‘000 t P.

Defra produces an annual Soil Nutrient Balance which estimates the phosphorus inputs and outputs of UK soils, enabling an estimate of the nutrient annual balance to be produced, which is a required in accordance with Eurostat and OECD reporting requirements (Clothier, 2010). The results for phosphorus in 2009 are presented in Table 7. These results present a more recent picture of phosphorus flows within the agricultural subsystem in the UK. The principal inputs are livestock manure (171 kt P), inorganic (or mineral) fertilisers (56 kt P), and organic fertilisers, of which around 95% is from sewage sludge (Clothier, 2011). Roughly equal amounts of phosphorus are removed in harvested crops (99 kt P) and forage (116 kt P), giving an overall phosphorus surplus to UK soils in 2009 of 54 kt P (Clothier, 2010).

Table 7: The phosphorus balance for UK soils in 2009

Source: Clothier (2010).

Phosphorus inputs and outputs in 2009	Quantity (thousand tonnes of P)
Phosphorus inputs	**271**
• Fertilisers	93
○ Inorganic fertilisers	56
○ Total organic fertilisers (excluding livestock manure)	36
• Net input of manure	171
○ Cattle	105
○ Pigs	11
○ Sheep and goats	26
○ Poultry	25
○ Other livestock	3
Phosphorus outputs	**217**
• Total harvested crops	99
○ Cereals	75
○ Oil crops	12
○ Pulses and beans	4
○ Industrial crops	3
○ Other crops	4
• Total forage	116
○ Harvested fodder crops	6
○ Pasture	110
• Crop residues	2
Balance (inputs minus outputs)	**54**

The studies from Withers et al. (2001) and Clothier (2010) do not include estimates of phosphorus runoff and erosion into water bodies. White and Hammond (2006) estimate agricultural diffuse pollution to be 12.8 kt P/year, and UKWIR (2010) provide a similar estimate of 12.9 kt P/yr.

4.2.2.2 Wastewater Industry

As identified in Section 4.1.6, the UK water industry receives a considerable amount of phosphorus within wastewater, estimated at 48.4 kt P/yr Approximately half of this is removed into the sewage sludge, of which 70% is recycled to agricultural land (Water UK, 2010), which therefore suggests that around 17.2 kt P/yr of wastewater phosphorus is currently recycled to agricultural land.

Compared to phosphorus applications within mineral fertilisers (54 kt P/yr) (Clothier, 2010), this suggests that there is a sufficient amount of phosphorus within wastewater that is currently not being recycled (31.2 kt P/yr) and this could make a significant impact on UK phosphorus security if it could be used to replace imported fertilisers.

The results also suggest that that the industry is responsible for the largest phosphorus losses to UK waters, 24.2 kt P from WwTWs compared to 12.9 kt P/yr from agriculture (UKWIR, 2010). Increasing the amount of phosphorus recycled to address resource security concerns will also reduce the amount of phosphorus polluting water bodies.

4.2.3 Knowledge gaps

The knowledge gap identified was that there was no complete national-scale SFA study for phosphorus in the UK, and no analysis of the quantity of phosphorus in wastewater compared to other major flows. A complete SFA model for phosphorus in the UK food production and consumption system was designed for this research. The methods are detailed in Section 5.2, while the results are presented in Section 6.2 and discussed in Section 7.2.

Also, the SFA models are inconsistent between countries, making comparisons difficult. There is no standardised approach to producing national-scale SFAs, and no agreed sustainability indicators that could be used to compare results from different countries and monitor progress over time. The SFA model developed for the UK system follows an accepted layout, as shown in Figure 21. The development of sustainable indicators and a comparison between countries is included in Section 6.2.7.

4.3 Drivers of phosphorus scarcity

Guiding question: When would an increase in phosphorus recycling from wastewater be required to increase UK phosphorus security? What are the key global drivers of scarcity and timescales associated with each?

The purpose of this section is to determine when the UK water industry would be required to increase phosphorus recycling. This supports the overall aim of the thesis by revealing if the water industry will be required to increase phosphorus recycling in the future within timeframes that are relevant for current planning cycles. Establishing a relevant timeframe will require a critical assessment of the global drivers of phosphorus scarcity that would affect phosphorus security in the UK. This section presents a critical assessment of these key drivers, which includes the physical, geopolitical and economic drivers of scarcity. The focus of this section is on phosphate rock, as this is the primary source of phosphorus, and the assessment includes:

- The size of phosphate rock reserves and resources,
- The distribution of current reserves,
- The size and distribution of current production,
- The lifetime of remaining reserves based on the reserve-to-production (R/P) ratios,
- The future demand for phosphate rock,
- A peak in production of phosphate rock (known as peak phosphorus), and
- The price of phosphate rock.

From this literature review, it will be possible to determine when phosphorus scarcity will become an issue for the UK, and therefore the timeframes involved in developing a more sustainable resource management system to increase UK security. This then establishes the timeframe within which increased phosphorus recycling from wastewater will be required.

4.3.1 The size of phosphate rock reserves and resources

The most obvious cause for physical scarcity of a non-renewable resource such as phosphate rock is complete depletion, when all of the resource has been extracted from the ground. The size of the resource also affects other potential drivers of scarcity, such as peak production. This section intends to establish how much phosphate rock is available for extraction today, or could become available in the future.

Although finite, phosphorus is not a rare element. In fact, phosphorus is the eleventh most abundant element in the earth's crust (Johnston and Steen, 2000), which contains more than a billion billion tonnes of phosphorus at a concentration of around 0.1% phosphorus (Emsley, 2001, Brinck, 1977). Under certain conditions, which involves both chemical and physical processes that rarely occur simultaneously, and over millions of years, the concentration of P-bearing minerals increases and physical reworking of P-rich sediments concentrates the phosphorus further, forming phosphorite deposits, or phosphate rock, which is mined for fertiliser production (Filippelli, 2011). In some cases, this rock can be mined to extract the phosphorus. Phosphate rock can be either sedimentary or igneous, but around 80% of the phosphate rock produced today comes from sedimentary rocks (Van Kauwenbergh, 2010). This phosphate rock ore typically contains 5 – 13% phosphorus (Cordell and White, 2011).

The mined phosphate rock ore usually undergoes a beneficiation process involving a combination of washing and screening processes to remove impurities and lower grade ores, and produce phosphate rock concentrate, which has an increased phosphorus content and has reached a marketable standard (Van Kauwenbergh, 2010, Edixhoven et al., 2013). The phosphorus content of the beneficiated concentrate is often expressed in terms of P_2O_5, which contains 44% P, and commercial phosphate rock concentrates vary in grade from over 37% P_2O_5 (16% P) to less than 25% P_2O_5 (10.9% P) (Van Kauwenbergh, 2010). On average, the phosphate rock produced in 2012 contained 30.6% P_2O_5, or 13.4% phosphorus (IFA, 2012).

The mining and beneficiation process generates large quantities of unrecovered spoil, which contains around 20-30% of the mined phosphorus (Dawson and Hilton, 2011). However, as extraction technology improves, these large deposits of previously worthless rock may be transformed into valuable ore, as was the case with copper mining (West, 2011). Confusingly, both ores and concentrates are often referred to as simply 'phosphate rock', which can lead to errors being made.

Phosphate rock deposits are classified based on the economic viability of extraction, which depends on accessibility and quality of the mined rock, the extraction and processing costs, and the market price. The three broad classifications commonly used are reserves, base reserves, and resources, although for each of these there are often various subcategories such as measured, indicated, inferred and hypothetical. As shown below, the definitions of even these three broad terms are often unclear and inconsistent (Edixhoven et al., 2013).

- **Reserves** are defined by the United States Geological Survey (USGS) as "the part of the identified resource which could be economically extracted or produced at the time of determination" (USGS, 2011). However, the economic assumptions that are used to define reserves, such as the $/tonne, are unclear and inconsistent between countries and companies (Cordell and White, 2011). The USGS produces a mineral commodity summaries report each year, which includes estimates of global phosphate rock reserves and annual production, and estimates for the individual countries with the largest reserves or production. The latest USGS report (January 2013) contained reserve and production estimates for 21 individual countries, and a combined estimate for all other countries. The USGS often appears to express reserves as ore (Edixhoven et al., 2013), while production is expressed as marketable concentrate (Jasinski, 2013). However, Moroccan reserves were increased in 2011 in line with the estimates from the IFDC, which reported reserves as concentrate, and not ore (Van Kauwenbergh, 2010). Therefore, it is assumed that USGS reserves are reported as concentrate.

- **Base Reserves** are defined by the USGS as "the in-place, demonstrated portion of the total resource that is already economically available (reserves) or has a reasonable potential of becoming economically available within planning horizons beyond those that assume proven technology and current economics" (USGS, 2011). As with reserves, no actual price is specified. The USGS used to estimate the size of the reserve base within the mineral commodity summaries report. However, since the closure of the US Bureau of Mines (USBM) in 1996, the data upon which the latest reserve base estimates was based has not been updated and was considered too old to remain defensible, therefore reserve base estimates were discontinued in 2009 (USGS, 2010).

- **Resources** are defined by the USGS as "a concentration of material in or on the Earth's crust in such form and amount that economic extraction is currently or potentially feasible, which includes reserves and base reserves" (USGS, 2011). The IFDC defines resources as "phosphate rock of any grade, including reserves, that may be produced at some point in the future" (Van Kauwenbergh, 2010). However, this broad definition is criticised by Edixhoven et al. (2013) since it allows the possibility of any phosphate rock deposit being considered as a resource by not specifying a timescale or suggesting what the conditions of that future may be. The USGS quote a global phosphate rock resource figure within the mineral commodity summaries. However, it is not specified if this is phosphate rock concentrate or ore, so it is assumed to follow the same system used by the IFDC, being reported as ore. This can lead to confusion since reserves, which actually form part of the resource, are quoted as concentrate, while resources are quoted as ore, therefore the two are not directly comparable. Also, in general, resources have a lower phosphorus content and more impurities than reserves, which means that production of a tonne of phosphate rock from a resource would yield less elemental phosphorus compared to production of a tonne of phosphate rock from a current reserve deposit.

Reserve estimates are dynamic and can change for a number of reasons. They can increase with the discovery of new deposits and upgraded estimates of known deposits, or through a reclassification of base reserves or resources to economical reserves, which may occur as extraction and processing technology improve or the market price increases which makes previously uneconomic deposits become economically viable. Tilton (2003) suggests that when a company has more than 20 – 30 years left of reserves at current production rates then there is little incentive to invest significant sums of money in discovering additional reserves. However, as oil exploration programmes have explored most of the coastal basins around the world, it is believed that any large-scale discoveries of phosphate rock would have occurred already (UNIDO and IFDC, 1998).

Between 1996 and 2010, phosphate rock reserve estimates ranged between 11,000 and 18,000 Mt, with the 2010 estimate at 16,000 Mt. Before its discontinuation, the reserve base was estimated at 47,000 Mt (Jasinski, 2009). In January 2011 the USGS increased its reserves estimate to 65,000 Mt, more than a 4-fold increase (Jasinski, 2011), as shown in Figure 5.

This change was largely influenced by a report produced by the International Fertilizer Development Centre (IFDC) in September 2010 which reviewed the literature surrounding phosphate rock reserves and resources and suggested that previous estimates had significantly underestimated the size of these deposits. The IFDC estimated that there remained approximately 60,000 Mt of reserves (as concentrate) and 290,000 Mt of resources (as ore in-situ) (Van Kauwenbergh, 2010). In particular, considerable revisions were made to Morocco's estimated reserves, which were increased from the USGS 2010 estimate of 5,700 Mt to around 51,000 Mt. The increase to Morocco's estimated reserves accounted for almost all of the increase to the global reserves estimate; in fact compared to the previous USGS estimate, the combined total of reserves held by all other countries actually decreased by around 10% in the IFDC report.

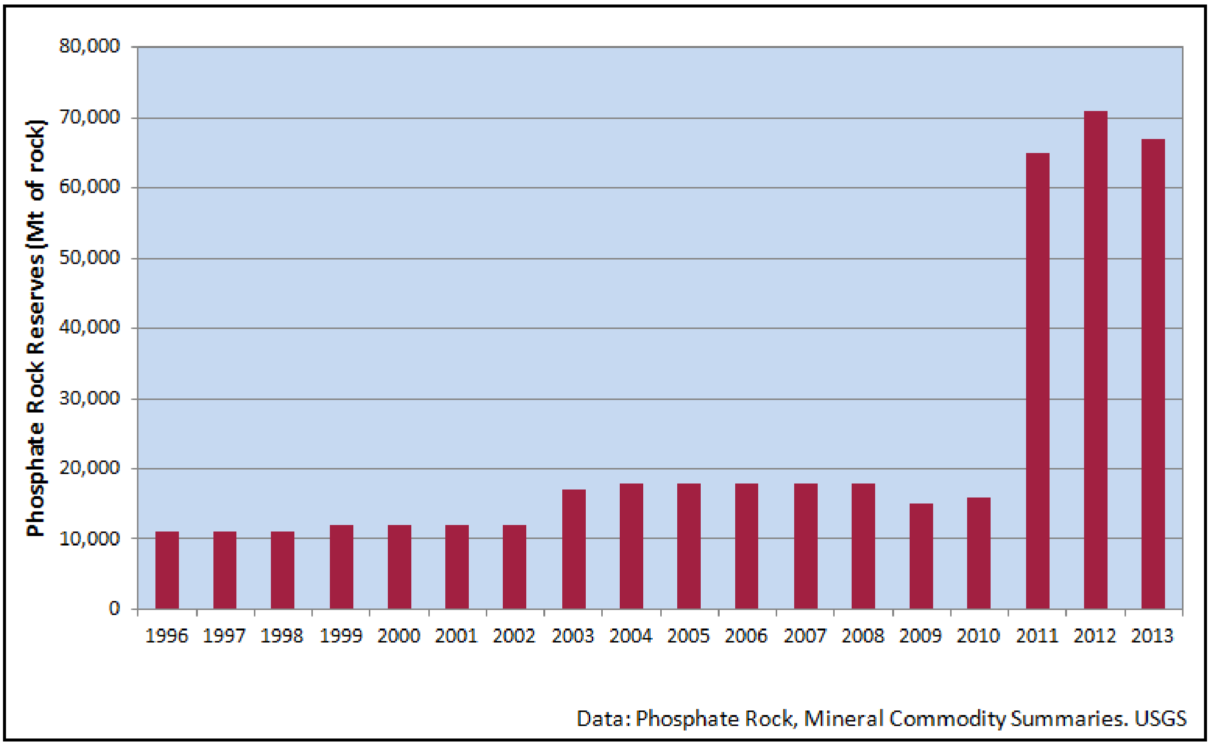


Figure 5: Historical U.S. Geological Survey phosphate rock reserve estimates.

Data Source: Phosphate Rock, Mineral Commodity Summaries, USGS.

The IFDC figures are not based on new discoveries but on data drawn from literature on global phosphate rock deposits, which has in itself become very limited since 1990 (Van Kauwenbergh, 2010). In order to estimate the size of Morocco's phosphate rock reserves, the IFDC used reports from Gharbi (1998) and OCP (1989). Hence, the revisions are based on literature that was previously overlooked or unavailable to the USGS, and was therefore not included in its reserve estimates for Morocco. The revisions were not based on new discoveries or studies. It should be noted that within the IFDC report it cautions that it is not known if all of Morocco's phosphate rock reserves are producible at today's costs (Van Kauwenbergh, 2010), which raises questions as to whether some of the quoted reserves should instead be considered as base reserves or resources. This report was criticised by the Global Phosphorus Research Initiative (GPRI, 2010), and Edixhoven et al. (2013) concluded that "the IFDC report presents an inflated picture of global reserves".

The dynamic nature of reserve estimates was demonstrated again in 2011, as 5,750 Mt of phosphate rock were found in Iraq (McPherson, 2011), and included within the USGS 2012 reserve estimates (Jasinski, 2012). This inclusion made Iraq the second largest country with phosphate rock reserves. However, these reserves were later removed in the USGS 2013 publication based on a report prepared jointly by the USGS and Iraqi Ministry of Industry and Minerals in 2012 (Jasinski, 2013), and it is likely that the reserves were downgraded to resources.

The latest USGS report (January 2013) estimates that globally there are 67,000 Mt of reserves and over 300,000 Mt over resources (Jasinski, 2013). At an average concentration of 13.4% P, this translates into around 9,000 Mt of P, or 9 x 10^9 tonnes of phosphorus in current reserves. This is much less than the 1 x 10^{18} tonnes of phosphorus estimated to be in the earth's crust (Emsley, 2001). Therefore, despite being incredibly abundant, only a fraction of the total phosphorus is currently available because of the costs and energy required to recover it. This fact is recognised and well understood for water, but less so for phosphorus (Cordell & White 2011).

The size of the phosphate rock reserves has a big impact on the drivers for physical scarcity. In particular, the remaining reserves affect the timeframe until complete depletion based on constant extraction rates (Section 4.3.4) and the peak production analysis (Section 4.3.6). There is currently a lack of information on the size and quality of global phosphate rock reserves and resources which makes it difficult to determine the appropriate timeframe for increasing phosphorus security. There is also inconsistent terminology used within the reporting of reserves and resources, which further complicates the issue. The dynamic nature of reserves implies that more phosphorus will become available in the future, which suggests that scarcity is not a short-term issue, but alternatively, the current reserve figure may have been overestimated, which would result in scarcity occurring much sooner.

4.3.2 The distribution of phosphate rock reserves

Global phosphate rock reserves are distributed amongst individual countries. An uneven distribution produces a geopolitical risk which could create regional scarcity and conflict. This in turn creates a resource security issue for the UK. The purpose of this section is to analyse the distribution of phosphate rock reserves in order to identify any security of supply risks for the UK.

Due to the specific conditions required for phosphate rock formation, which rarely take place in unison, the occurrence of phosphate rock formation is limited both temporally and geographically, resulting in a few massive phosphorite formations, known as "Phosphorite Giants", that make up the bulk of phosphate rock reserves (Filippelli, 2011). These reserves are held by only a handful of countries. Therefore, there is also a geopolitical aspect to the phosphate rock situation which could affect phosphorus security in the UK.

The revisions to USGS data based on the IFDC report released in September 2010 have revealed an increased concentration of phosphate rock reserves to just a handful of countries (see Figure 6). It is now estimated that Morocco has 74% of the world's reserves, with 50,000 Mt of reserves, whilst the top 5 countries with the largest reserves have combined control of 88% of the world's reserves (Jasinski, 2013).

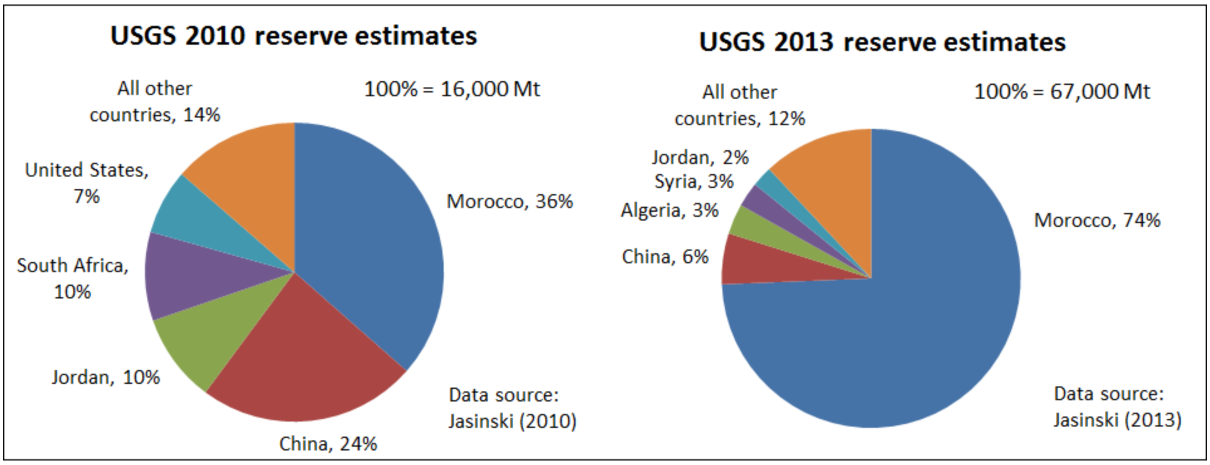


Figure 6: U.S. Geological Survey reserve estimates for 2010 and 2013
Data Source: Jasinski (2013).

The Moroccan mining industry is controlled by the Office Chérifien des Phosphates (OCP), which is a state-owned group, with Morocco's King Mohammed VI the unofficial overseer (Rosemarin, 2004, Westenhaus, 2010). This generates an interesting situation where one person effectively controls around three quarters of the global phosphate reserves. Moreover, some of these reserves are situated in Western Sahara, an independent territory that has been occupied by Morocco since 1975 (Rosemarin et al., 2009). The International Fertiliser Development Centre (IFDC) estimate that around 1,100 Mt of Morocco's 50,000 Mt, are located within the Bu Craa region of Western Sahara (Van Kauwenbergh, 2010). This amounts to around 2% of Morocco's total reserves. Production from Western Saharan deposits is estimated to be between 5-10% of OCP's phosphate rock extraction (OCP, 2009). However, exploiting mineral resources in Non-Self-Governing Territories, such as Western Sahara, against the wishes and best interests of the people is illegal under international law (Corell, 2002), and consequently some Australian and Scandinavian firms have stopped importing Moroccan phosphate rock (Rosemarin et al., 2009, Cordell, 2010).

The extent of the concentrated distribution of phosphate rock reserves is demonstrated in Figure 7, with the final column being the combination of all other countries in the world. Of particular note is the absence of India (soon to be the world's most populous country) and any of the Western European countries. Finland is the only West European country with commercial deposits (Johnston and Steen, 2000) and India's low-grade phosphate rock deposits are unsuitable for fertiliser production (Rosemarin, 2004). It is anticipated that regional scarcities will occur much sooner than absolute scarcity, especially if phosphate-rich countries ban exports to conserve domestic supplies, and powerful countries move to secure remaining reserves with long-term trade contracts or military force (de Haes et al., 2009). It is for this reason that the situation with phosphate rock has been referred to as a "geostrategic ticking time-bomb" (Vaccari, 2009).

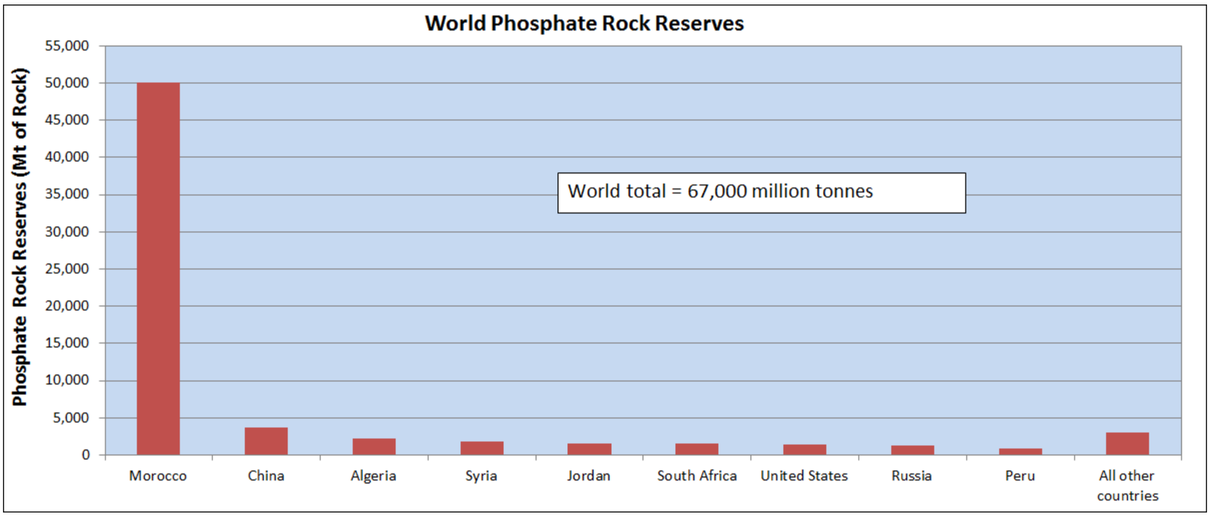


Figure 7: Distribution of world phosphate rock reserves.

Data source: Jasinski (2013)

The geographical concentration of phosphate rock can also be compared to that of oil, a key, non-renewable resource that is also concentrated within just a handful of countries. Figure 8 demonstrates that phosphate rock reserves are much more concentrated than oil reserves. Morocco has been referred to as the "*Saudi Arabia of Phosphorus"* due to the large amount of reserves that it controls (Vaccari, 2009). However, based on the latest USGS figures, Morocco would be better compared to the whole of OPEC, rather than just Saudi Arabia, as the proportion of phosphate rock reserves it controls is equivalent to the proportion of oil reserves held by all 12 member states of OPEC combined, around 72% (BP, 2013). The potential threat to resource security presented by a concentrated supply was witnessed during the 1973 oil crisis when the Arab member states of OPEC imposed an oil embargo against the US, which had the effect of quadrupling world oil prices and contributed towards a global economic recession.

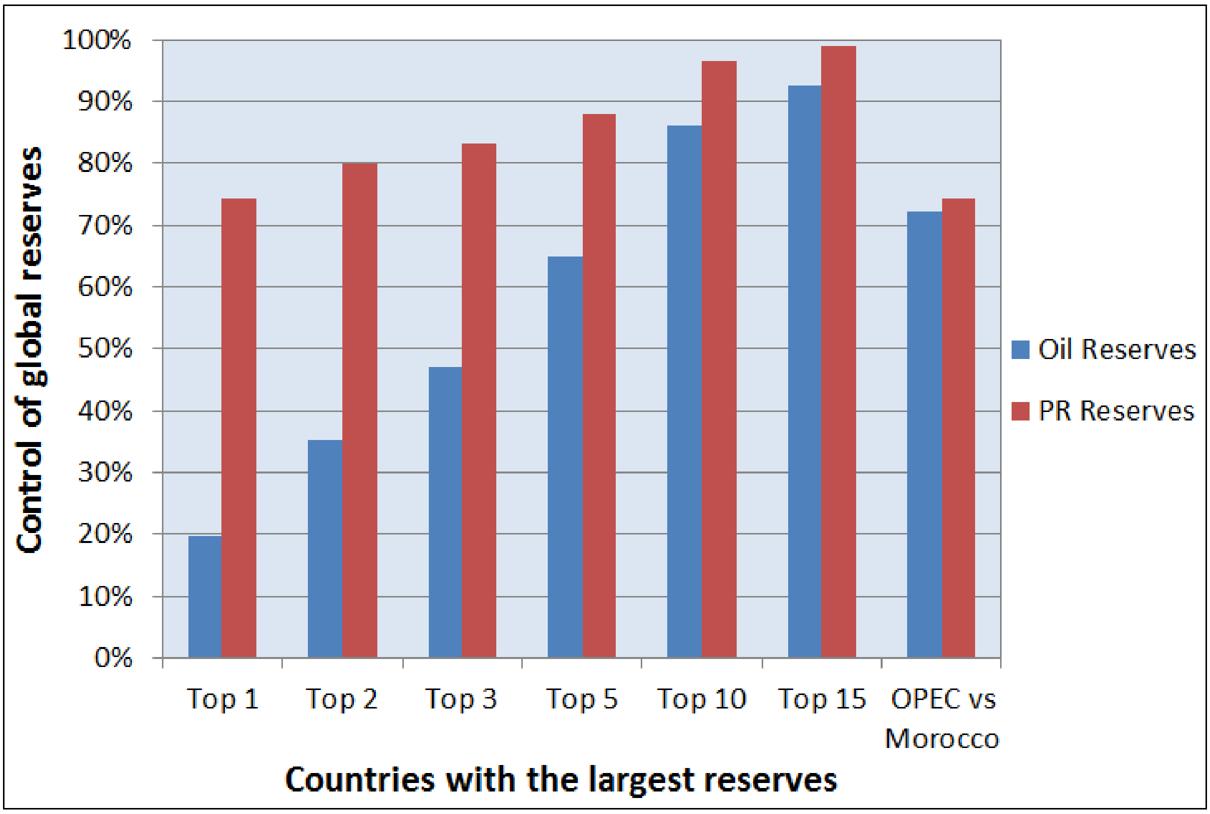


Figure 8: A comparison of the distribution of phosphate rock and oil reserves.
Data source: BP (2013) and Jasinski (2013).

This section has demonstrated that the distribution of phosphate rock reserves is concentrated to just a handful of countries. This presents the geopolitical risk that countries could impose export restrictions or use their market power to influence the price of phosphate rock, therefore creating physical and economic scarcity. Disruptions to supply from key producing countries due to natural disasters or conflicts could also create scarcity. Based on this information, it is concluded that the distribution of reserves presents a short-term (<50 years) security of supply risk for the UK.

4.3.3 Phosphate rock production

The rate of extraction of phosphate rock is a determining factor as to when physical scarcity, including absolute depletion and peak production, might occur. Therefore, this section assesses the production of phosphate rock. This includes the historical production to reveal the rate of growth, the current level of production to enable the lifetime of remaining reserves to be calculated through the reserve-to-production ratio (Section 4.3.4), and the distribution of production to reveal the extent of security of supply concerns.

Mineral phosphorus fertilisers were first produced from bone meal in 1842, producing superphosphate, which boosted crop yields and was suggested as an improved method of fertilising the soil (Emsley, 2001). Shortly afterwards, fertilisers were also being manufactured from guano (bird droppings that have accumulated over thousands of years), with imports beginning in 1847 (CIWEM, 2012), and Thomas slag (or phosphatic slag), a waste product from the steel industry (de Haes et al., 2009). By 1850, superphosphate was being produced by treating phosphate rock with sulphuric acid, which produced phosphoric acid (Emsley, 2001). An improved fertiliser, known as triple superphosphate, was also produced around this time by dissolving phosphate rock in the phosphoric acid (Emsley, 2001). Many guano deposits have since been depleted (Filippelli, 2011), and now phosphate rock represents the major, and only new raw material supply for fertiliser production (UNEP, 2011). It is estimated that more than 90% of the phosphorus extracted from phosphate rock is used in agriculture (Brunner, 2010).

The discovery and production of mineral fertilisers, in particular fertiliser derived from phosphate rock, allowed crop yields to be massively increased. This played a crucial, but often unappreciated role in the green revolution in which global food production was increased substantially (Elser and White, 2010). The increasing agricultural productivity and food production was accompanied by rapid increases in the human population, which was then able to produce more food, therefore creating a positive feedback system that consumes more and more natural resources, including phosphorus (Brown, 2003). As the primary source of phosphorus, phosphate rock consumption has therefore increased alongside population growth, as shown in Figure 9, and this trend is expected to continue.

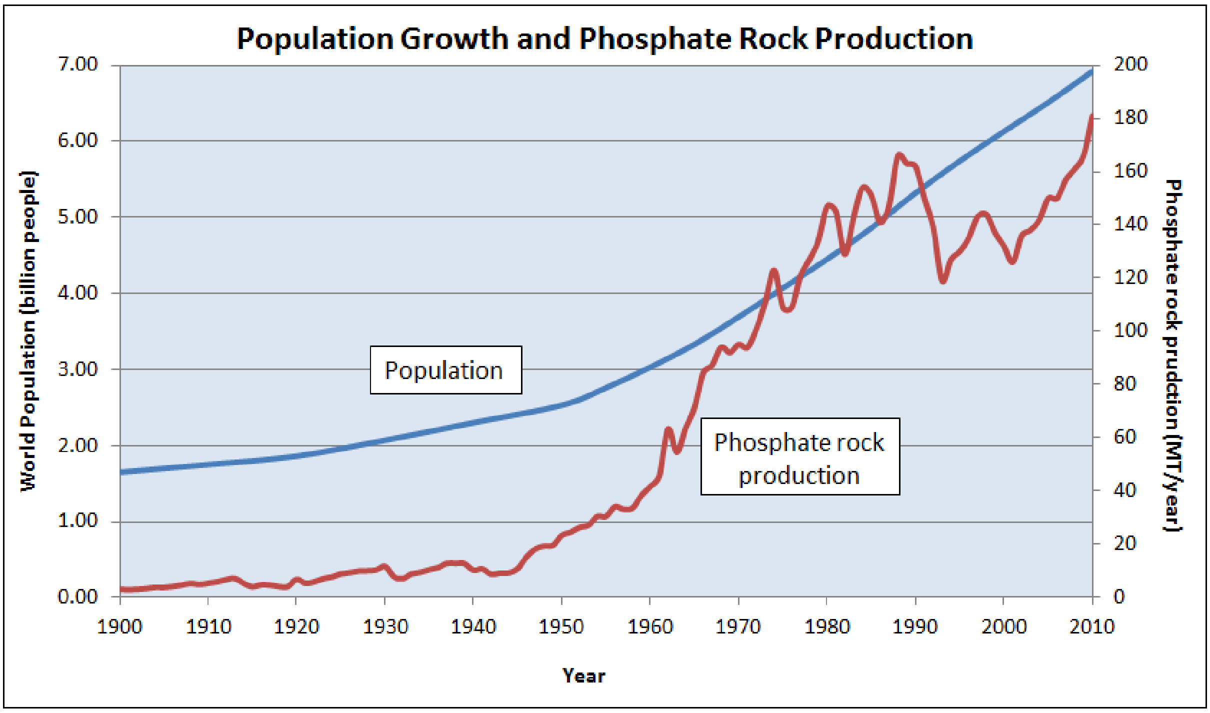


Figure 9: The relationship between population growth and phosphate rock production. Data source: Population – UN (1999) for 1900-1940, UN (2013b) for 1950-2010; Phosphate rock production – Buckingham and Jasinski (2012).

USGS historical production data suggests that around 7,000 Mt of phosphate rock was produced between 1900 and 2010, with production increasing on average by 3.7% per year (Buckingham and Jasinski, 2012). As shown in Figure 9, phosphate rock production peaked in 1989 and declined for several years, partly due to the collapse of the Soviet Union and decreased fertiliser demand in Western Europe and North America (Cordell et al., 2009a). However, rising demand over the last 10 years has seen annual production increase again by around 3% per year, reaching around 176 Mt in 2010 (Jasinski, 2010).

Similar to the situation with phosphate rock reserves, global production is dominated by just a handful of countries, as shown in Figure 10. Historically, the US was the largest phosphate rock producer, responsible for almost a third of global production between 1900 and 2012 (Buckingham and Jasinski, 2012). However, production in the US peaked around 1980 (Buckingham and Jasinski, 2012), and China surpassed the US as the world's largest phosphate rock producer in 2006, now producing around 43% of the global production (Jasinski, 2007, Jasinski, 2013). In an effort to secure domestic supplies during the 2008 price spike, China imposed a 135 percent export tariff on its phosphate rock, which effectively stopped exports (Elser and White, 2010). If phosphorus becomes scarce in the future, it is possible that this behaviour could become common for producing countries in order to protect domestic supplies. This would have a significant impact on many countries, including the UK, that have no phosphate rock reserves.

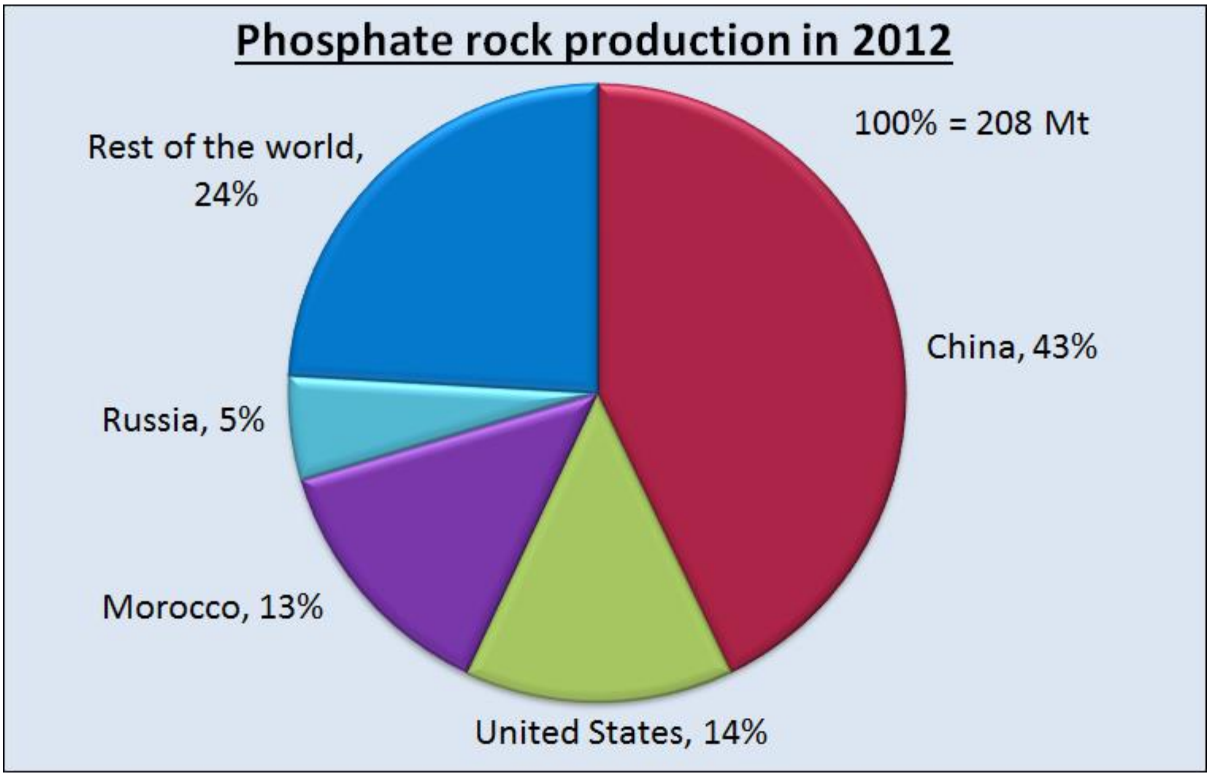


Figure 10: Share of world phosphate rock production in 2012.
Data source: Jasinski (2013).

Morocco is a relatively small consumer of phosphorus, so most of the phosphate rock that is produced is destined for international markets. In fact, despite producing only 13% of the global production (Jasinski, 2013), Morocco's share of the export market is currently over 35% (OCP, 2010). Morocco is expected to nearly double its production capacity between 2011 and 2017 (Jasinski, 2012), which significantly increase its share of global production. This may affect security of supply if the UK becomes increasingly reliant on a single country.

The concentrated production of phosphate rock can also be compared to oil production. This is useful since oil production is dominated by very few countries and has been proven to be vulnerable to supply disruptions and price spikes in the past. As shown in Figure 11, the production of phosphate rock is more concentrated than oil production for the largest 10 producers. China is the largest producer of phosphate rock, with 43% of global production in 2012 (Jasinski, 2013), which can be compared to Saudi Arabia, the world's largest oil producer in 2012, with 13.3% of global oil production, and OPEC which produced 43.2 % of oil production (BP, 2013).

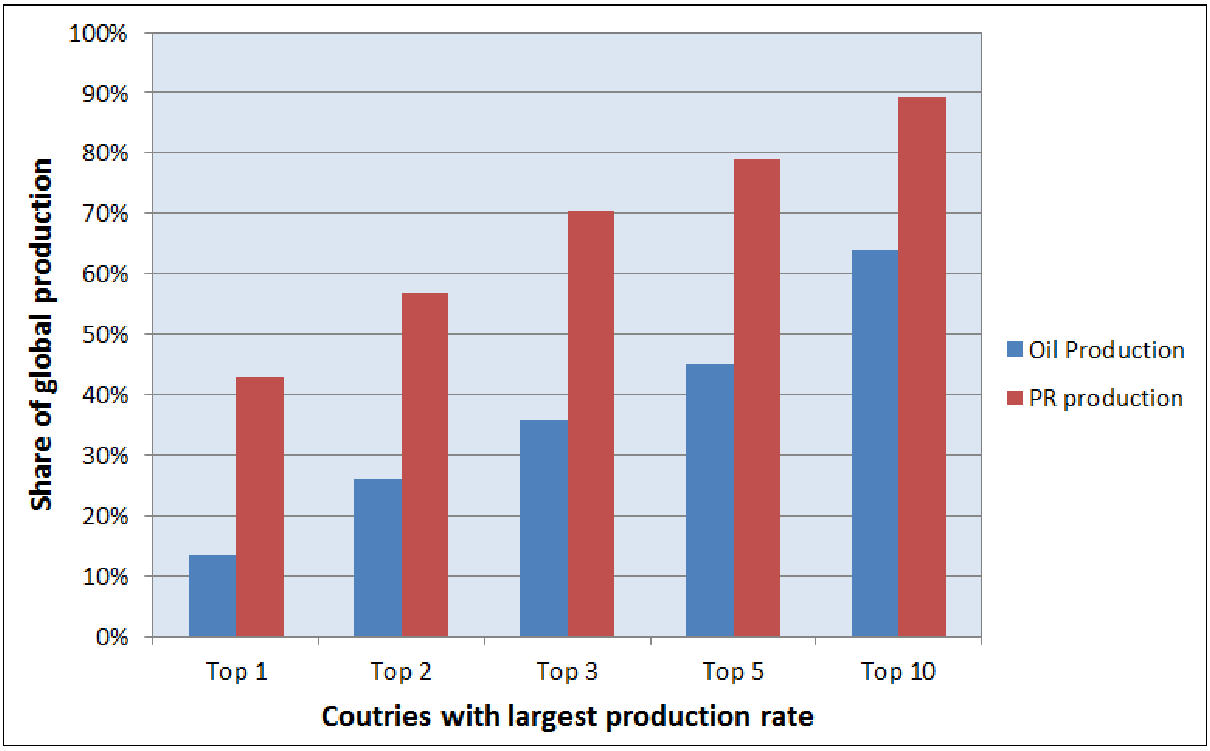


Figure 11: Comparing the distribution of phosphate rock and crude oil production.
Data sources: BP (2013) and Jasinski (2013).

Global phosphate rock production in 2012 is estimated at 207.5 Mt per year, with China producing 43% and the world's top three producers (China, US and Morocco) together producing over 70% (Jasinski, 2013). Approximately 7 billion tonnes of phosphate rock were produced between 1900 and 2010, and at current extraction rates, the next 7 billion tonnes will be mined before 2050 (Buckingham and Jasinski, 2012). However, world production capacity is projected to increase from 220 Mt/year in 2012 to 256 Mt/year in 2016, with most of the production increases occurring in Morocco (Jasinski, 2013).

Figure 12 shows that the quality of mined phosphate rock is declining. This is due to the best quality deposits being mined first and also as improved extraction technology or increased market prices allow lower grade deposits to be mined. The reduced grade of phosphate rock means that more rock will have to be produced to yield the same amount of phosphorus. This is worsened by the fact that recovery rates are inversely proportional to grade (Van Kauwenbergh, 2010). The lower grade rock generally contains higher impurity contents, which increases processing problems and results in higher costs (Van Kauwenbergh, 2010).

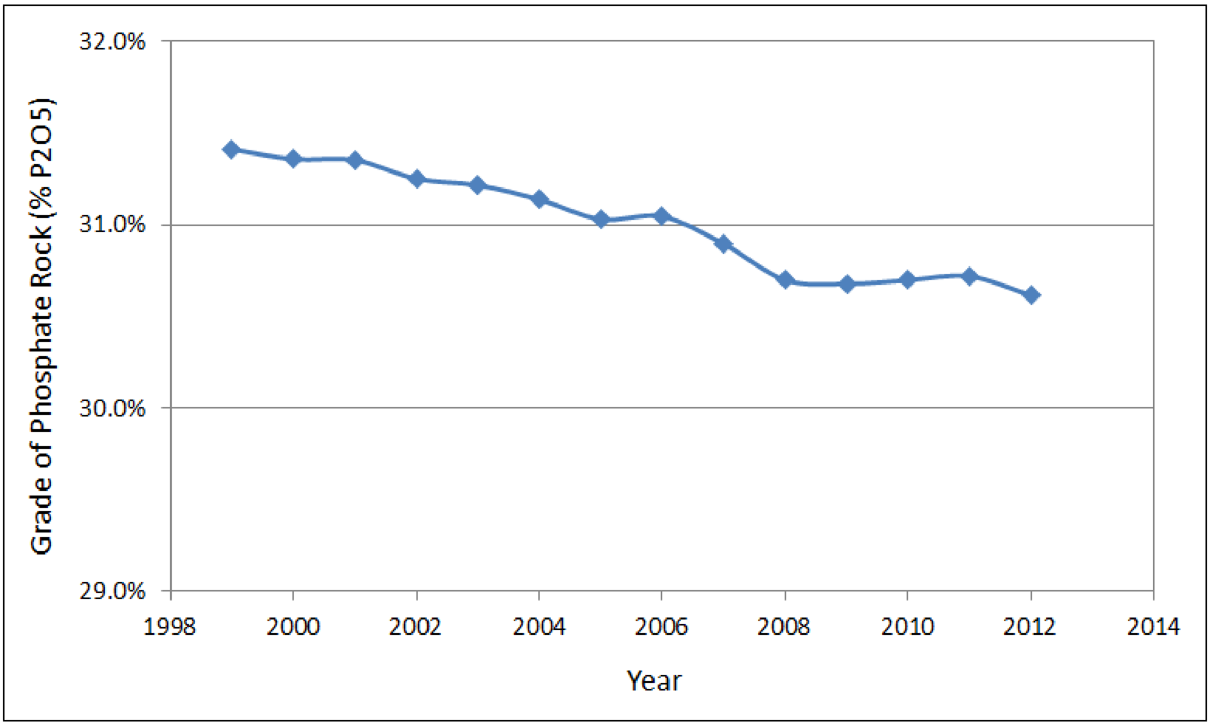


Figure 12: The declining grade of phosphate rock produced between 1999 and 2012.
Data Source: IFA (2012)

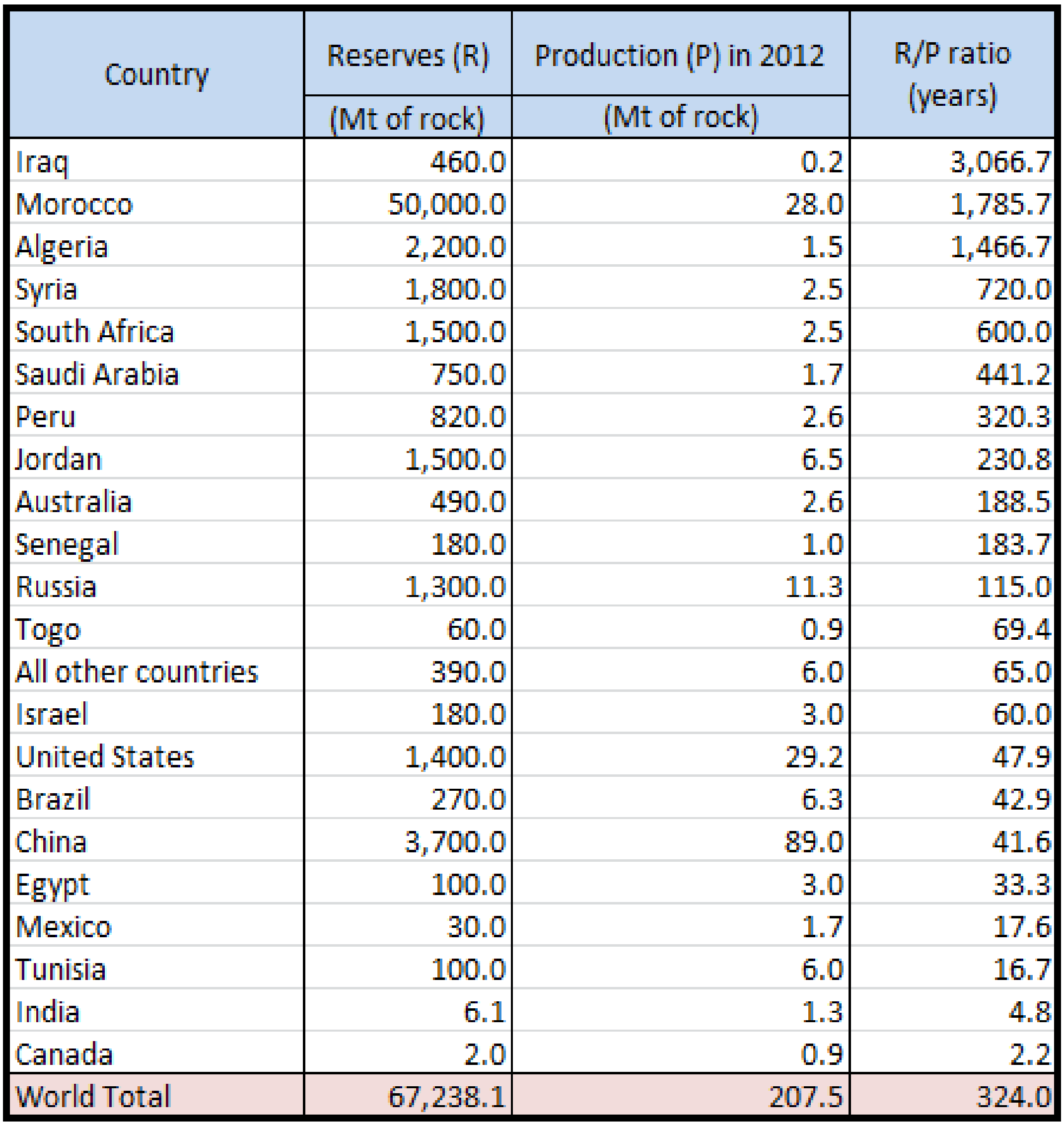
This section has revealed that the distribution of phosphate rock production is also incredibly concentrated to just a few countries. As with the distribution of reserves, this presents a geopolitical risk, with certain countries being able to influence the market price and restrict exports. This section also suggests that the phosphate rock production system is not resilient, since there is not a diverse range of countries producing phosphate rock that could compensate for a disruption in another country. Therefore, the production of phosphate rock is a short-term (<50 years) security of supply concern. The absolute depletion of phosphate rock reserves based on current production rates is included in the following section.

4.3.4 Reserve-to-production ratio

A reserve-to-production (R/P) ratio gives an indication of the lifetime of the reserves at current production rates. This section identifies the current global R/P ratios to reveal a timeframe for complete depletion. Also, the individual country R/P ratios are identified to determine the depletion rates of reserves within individual countries, which may also cause global scarcity and presents a security of supply issue for the UK.

Using the 2013 USGS figures, there are approximately 67,000 Mt of global phosphate rock reserves, and production in 2012 was estimated at 208 Mt, suggesting a lifetime, or R/P ratio, of 324 years at constant extraction rates (Jasinski, 2013). However, reserves and production rates vary amongst producing countries, and individual countries therefore operate different R/P ratios, as shown in Table 8.

Table 8: Phosphate rock reserve-to-production (R/P) ratios for individual countries. Data source: Jasinski (2013).



Country	Reserves (R)	Production (P) in 2012	R/P ratio (years)
	(Mt of rock)	(Mt of rock)	
Iraq	460.0	0.2	3,066.7
Morocco	50,000.0	28.0	1,785.7
Algeria	2,200.0	1.5	1,466.7
Syria	1,800.0	2.5	720.0
South Africa	1,500.0	2.5	600.0
Saudi Arabia	750.0	1.7	441.2
Peru	820.0	2.6	320.3
Jordan	1,500.0	6.5	230.8
Australia	490.0	2.6	188.5
Senegal	180.0	1.0	183.7
Russia	1,300.0	11.3	115.0
Togo	60.0	0.9	69.4
All other countries	390.0	6.0	65.0
Israel	180.0	3.0	60.0
United States	1,400.0	29.2	47.9
Brazil	270.0	6.3	42.9
China	3,700.0	89.0	41.6
Egypt	100.0	3.0	33.3
Mexico	30.0	1.7	17.6
Tunisia	100.0	6.0	16.7
India	6.1	1.3	4.8
Canada	2.0	0.9	2.2
World Total	67,238.1	207.5	324.0

Morocco has the largest reserves and a relatively small production, which has a large influence over the global R/P ratio. Morocco's reserves would last over 1,700 years at constant extraction rates, and this increases the global R/P average. However, half of the countries included in Table 8 have R/P ratios less than 70 years, which includes the joint category for 'All other countries', and also the United States and China, which are currently the world's largest phosphate rock producers. In fact, the production from these countries with R/P ratios less than 70 years was estimated at 147 Mt in 2012, which is around 71% of the overall production.

Although this simple measure is widely used to estimate future resource scarcity, it does have some flaws since both terms in the equation (R and P) are not constant. As previously discussed, reserves are dynamic, and can increase or decrease over time depending on a number of factors, and production is also not constant, generally being expected to increase in the future to meet the growing demand for food and fertilisers. Despite the criticisms of R/P ratios, it remains useful as an indicator of potential scarcity (Vaccari and Strigul, 2011).

This section has revealed that the global depletion of phosphate rock reserves is not expected to result in physical scarcity in the short- or medium-term at constant extraction rates. However, as discussed in the following section, the demand for phosphate rock is increasing, which will increase the rate of depletion. More importantly, this section reveals that most producing countries will deplete their reserves this century, including those countries producing most of the world's phosphate rock. This will increase the concentration of reserves and production to fewer countries, generating increased geopolitical risks, reduced resilience, and hence increased security of supply concerns. No analysis was identified to determine the impact this will have on the future distribution and production of phosphate rock reserves. Therefore, this has been identified as a knowledge gap (Section 4.3.9) and will be investigated further.

4.3.5 Future demand and production

The future demand for phosphate rock will influence future production. This will affect the global R/P ratio (Section 4.3.4) and could lead to a peak in phosphate rock production (Section 4.3.6), both of which could create global scarcity and affect security of supply in the UK. This section establishes what the demand for phosphorus and phosphate rock will be in the future.

The future demand for phosphate rock is linked to food production, since around 90% of the phosphorus derived from phosphate rock is used in agriculture (Brunner, 2010). The demand for food is expected to increase in the future with the main drivers being increasing populations and changing diets. The human population rapidly increased during the 20th Century from 1.7 billion in 1900 to 6.1 billion in the year 2000 (UN, 1999). The current population is now estimated to be around 7.2 billion people (UN, 2013b). This rapid population growth is expected to continue, reaching 8.1 billion by 2025, 9.6 billion by 2050, and 10.9 billion by 2100 (UN, 2013b). This will accelerate the depletion of non-renewable resources such as phosphate rock. Also, as developing countries become more prosperous, the dietary preferences of the people living in those countries changes to diets that contain more meat and dairy products. This accelerates the demand for food, fertilisers and phosphate rock beyond population growth. There is also a ‘silent’ demand from the world’s poorest farmers with nutrient deficient soils who cannot afford fertilisers (Cordell, 2010) and a need to provide food for the 842 million people in the world who are suffering from chronic hunger (FAO, 2013). In total, it is estimated that the demand for food could increase by 40% by 2030 and 70% by 2050 (Foresight, 2011). Borlaug and Dowswell (2003) estimated that harvests would have to expand by 50% by 2030 and food production would have to double during the 21st century.

The increase in food production and the development of non-food crops, such as biofuels, is expected to increase the future demand for fertilisers. The Food and Agricultural Organisation of the United Nations (FAO) expects fertiliser demand to increase by around 1 – 1.5% per year to 2030 (FAO, 2000, FAO, 2002), slowing to 0.9% per year between 2030 and 2050 (FAO, 2002). The increase in fertiliser demand will translate into increased demand for phosphorus and phosphate rock. Cordell et al. (2009b) estimate that the demand for phosphorus will grow by 2% per year to 2050. The growth in demand for phosphorus may translate into a larger growth rate for phosphate rock, since the quality of rock is decreasing (IFA, 2011), which suggests that more phosphate rock will need to be mined in the future to produce the same amount of phosphorus.

Several studies have attempted to estimate the future demand for phosphorus and phosphate rock in order to determine a more accurate assessment of the lifetime of reserves, rather than simply relying on a constant production scenario. Table 9 presents some of these longer term estimates for future phosphate rock demand. For ease of comparison, the figures have all been converted into quantities of phosphate rock, as opposed to weights of P_2O_5 or P, by assuming that the quality of phosphate rock is 30% P_2O_5 (which contains 44% P). This conversion is based on IFA statistics which suggest that the grade of phosphate rock produced in 2009 was 30.6% P_2O_5 (IFA, 2011).

Table 9: Future demand for phosphate rock

Information source	Assumptions	2020	2050	2100
(de Haes et al., 2009)	'Trend' scenario: increasing production of 0.7% per year from 2010 levels.	-	195 Mt	-
(Cordell et al., 2009b, Cordell, 2010)	'Probable' scenario: growth of 2% per year to 2050 (64 Mt P), and 0.5% until 2100 (82 Mt P). Assume 60% of P is from phosphate rock.	-	294 Mt	377 Mt
(Steen, 1998)	'Realistic' scenario – 70 Mt P_2O_5 by 2050.	-	233 Mt	-
(Smit et al., 2009)	Scenario B - allows for biofuels, as well as increasing efficiency and recycling, 26.2 Mt P by 2020, and 32.9 Mt P by 2050.	198 Mt	249 Mt	-
(Mew, 2011)	250 – 280 Mt by 2050. Production reaches a plateau of 250 million tonnes per year.	-	250 Mt	250 Mt

Based on all of the information included within this section, it is concluded that absolute physical scarcity caused by complete depletion of phosphate rock reserves will not be encountered within 200 years. This is a relatively small timescale compared to the time of human civilisation, but is considered beyond current planning horizons and so is unlikely to drive phosphorus as a resource issue for the UK water industry in the short or medium term.

4.3.6 Peak phosphorus

Peak theory suggests that the rate of production of a non-renewable resource cannot continue to increase indefinitely, but instead will eventually be constrained by supply as the best quality and most accessible deposits become depleted, making it increasingly difficult and costly, and eventually impossible, to further increase production. At this point, production reaches a maximum rate, and demand may then begin to exceed supply, resulting in rapid price increases and resource scarcity. The production curve of a non-renewable resource is estimated to roughly follow a symmetrical bell-shape, so that a peak in production occurs when half of the reserves remain in the ground. Therefore, this critical point is encountered much sooner than depletion of the entire resource (Cordell and White, 2011). The intention for this section is to determine if the peak production theory is applicable to phosphate rock, as this could create scarcity issues for the UK long before the complete depletion estimated in Section 4.3.4.

The peak production theory of supply-sided constraints on global production was first proposed by M. King Hubbert in 1949 to suggest a peak in oil production, or ‘peak oil’ (Hubbert, 1949). The peak oil production curve is shown in Figure 13. The area beneath the graph is known as the Ultimate Recoverable Resource (URR), which is the total amount of the resource that will be produced, including reserves that have already been extracted, existing reserves, future discoveries, and reclassifications of resources to reserves.

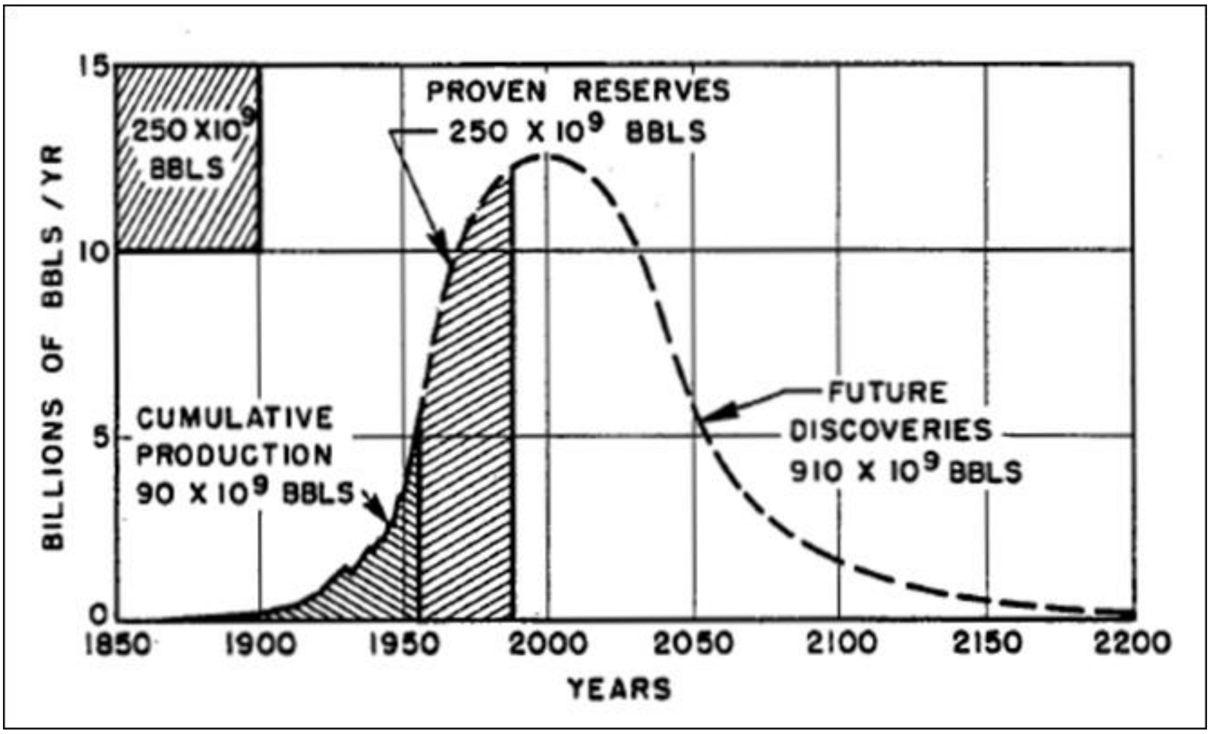


Figure 13: Peak oil production.
Source: Hubbert (1956).

Based on the theory that the growing demand for all critical resources will exceed economically available supply at some point, the peak theory has been applied to other non-renewable resources such as other fossil fuels, metals and minerals, and even renewable resources such as water, soil and food (Cordell and White, 2011). In particular, the analysis has also been used to determine a peak in phosphate rock production, commonly known as 'Peak Phosphorus'. Based on a cumulative historical production of around 6,700 Mt and the USGS 2008 reserves estimate of 18,000 Mt, Cordell et al. (2009a) used an URR of approximately 24,700 Mt and a Gaussian distribution from Laherrère (2000) to predict that peak phosphorus will be reached in 2033 at 29 Mt P/year, as shown in Figure 14. This is approximately 221 Mt of phosphate rock per year at 30% P_2O_5 content. However, phosphate rock production in 2013 is estimated to be greater than this at 224 Mt (Jasinski, 2014), and world production capacity is projected to increase to 256 Mt/year in 2016 (Jasinski, 2013).

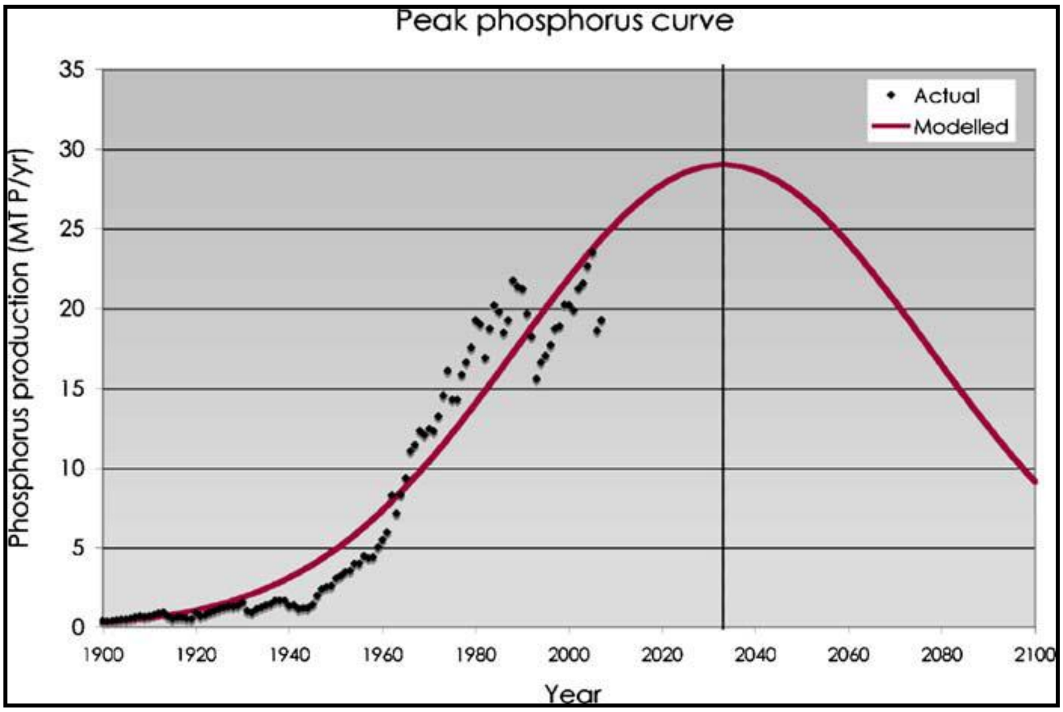


Figure 14: Peak Phosphorus Curve
Source: Cordell et al. (2009a)

The area under the production curve in the peak phosphorus analysis in Figure 14 includes the total historical production, plus reserve estimates from the USGS. However, the true URR would also include future discoveries or reclassifications, therefore this does not represent the true URR unless it assumes that no further phosphate rock reserves will be discovered or reclassified as reserves in the future. This is considerably different to the peak oil analysis in Figure 13, where most of the area under the graph is allocated to future discoveries. This omission may lead to an underestimate of when peak phosphorus could occur. Estimates of future discoveries or reclassifications are also highly uncertain.

Therefore, since the area under the graph is not known, the bell-shaped curve is not considered a robust method for predicting a peak in production (Vaccari and Strigul, 2011).

If the area under the production curve represented the true URR, then revisions to reserve estimates would not increase this area, since it would simply shift future discoveries and reclassifications to current reserves, without changing the actual size of the URR. Since the peak phosphorus analysis above uses only the current reserves in the URR, which are dynamic, changes to these reserves can significantly affect the results of the analysis. The revisions to phosphate rock reserve estimates following the release of the IFDC report (see Section 4.3.1) mean that the area under the production curve used in the Peak phosphorus analysis has increased significantly. This changes the results considerably. An updated version of the peak phosphorus analysis has been produced using the IFDC reserve estimate of 60,000 Mt and suggests that peak phosphorus will still be reached before the end of the century (Cordell et al., 2011). As shown in Figure 15, the peak year is estimated to occur between 2051 and 2092, with the midpoint being 2072. No maximum production rate is specified within the analysis.

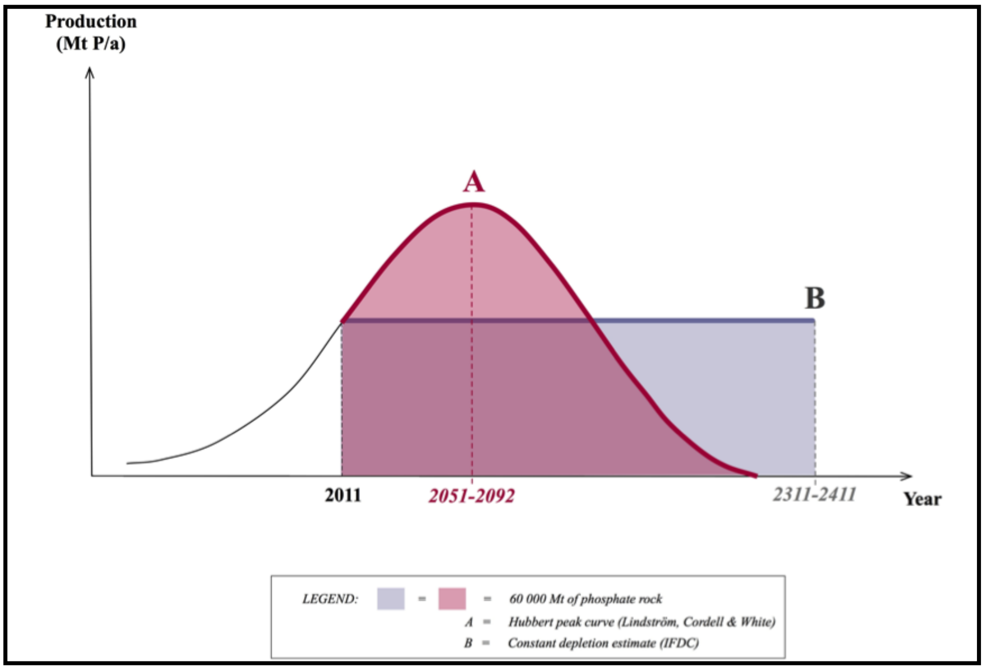


Figure 15: Updated peak phosphorus curve.

Source: Cordell et al. (2011).

Mew (2011) suggests that to reach a peak this century, phosphate rock production would have to increase to around 700 Mt/year by 2080, which is around three times greater than current production. This is also much greater than the estimates for future demand outlined in Table 9, which range from 195 Mt/year to 294 Mt/year by 2050. This suggests that production will not reach the level required to produce a supply-sided peak during the 21st Century. However, increasing production from 207.5 Mt in 2012 (Jasinski, 2013) to 700 Mt by 2080 with a linear increase in production would result in the depletion of almost 30,000 Mt of reserves during that time. This represents approximately half of the remaining reserves being depleted between now and the peak year, which does not fit with the shape of the graph shown in Figure 15. Therefore, the level of production required to reach a peak this century is likely to be lower than the 700 Mt/year estimated by Mew (2011). Furthermore, a peak in production that occurred after 2080, but before 2100, could occur at an even lower production rate. However, although the peak production value could be lower than 700 Mt/year predicted by Mew (2011), it is still expected to be higher than the production estimates from Table 9, which suggests that it will not be reached during the 21st Century.

It has also been suggested that the demand for phosphate rock could peak around mid-century, mainly caused by a peak in human population (Smit et al., 2009, Mew, 2011). This would lead to a demand-sided peak in production, which would not produce the same negative outcomes that are created through a supply-sided peak. However, supply issues could still arise at a later date with continued extraction. Mew (2011) suggests that demand will plateau at around 250 Mt, less than half the amount required to create a peak this century, and that this rate of production could be sustained for a further 168 years before supply constraints arise. However, the global population is projected to continue growing throughout the 21st Century (UN, 2013b), as shown in Figure 1, and, combined with the increasing per capita consumption, increasing demand for fuel crops, and the declining quality of phosphate rock, this suggests that the demand for phosphorus and phosphate rock will not plateau this century. Vaccari and Strigul (2011) suggest that a number of indicators, such as resource lifetime estimates and trends in costs and grades, all point toward increasing scarcity and suggest that a peak may be looming, although no timeline is estimated.

Similar to peak oil production, a peak in phosphorus from phosphate rock production is expected to resemble an extended and ‘lumpy’ plateau, rather than a definitive peak (Cordell and White, 2011). This is expected as the lack of alternatives would create a strong pressure to maintain production (Vaccari and Strigul, 2011). Roberts (2005) warns that "the edge of a plateau begins to look like a cliff", meaning that maintaining a plateau will result in a steeper eventual decline in production, which buys time but could be more problematic in the future once the decline begins.

As demonstrated, there is a great deal of debate surrounding the peak phosphorus issue with little consensus as to when the peak will occur. An improved estimate of global phosphate rock reserves and resources, and better estimates of future demand would be useful to determine when a supply-side peak could be reached. This information could also then be used to determine if a demand-side peak or plateau will delay this event, and also when this driver could cause scarcity for the UK. However, such an analysis is beyond the scope of this thesis. Without this analysis, it is suggested that peak phosphorus event is a medium- to long-term risk (>50 years).

4.3.7 Price of phosphate rock

The price of phosphate rock is likely to increase as phosphate rock reserves are depleted and become scarce. This would lead to increased exploration for new deposits, the opening up of new mines with advanced mining methods such as underground mining, and a reclassification of deposits that were previously marginally economic but are now economically viable (Van Kauwenbergh, 2010). The end result would be an increase in phosphate rock reserves. However, as well as physical scarcity, there can also be an economic scarcity where the price of phosphorus and fertilisers becomes too expensive for farmers to afford. This is already the case for many of the world's poorest farmers, particularly those in Africa, where the average application rate of fertilisers is less than 1 kg P/ha (compared to 7.4 kg/ha in the UK (Defra, 2013)). This practice is actually depleting soil phosphorus levels and threatening future food security in those regions (Smit, 2011). Therefore, increases to the market price of phosphate rock, which would increase the amount of reserves, would have the undesirable effect of making even more poor farmers around the world unable to afford fertilisers. Price rises would also impact agricultural practices and food prices in the UK.

The price of phosphate rock remained fairly constant between 1980 and 2006, fluctuating around \$40/tonne (World Bank, 2012). However, in 2007/08 the price of phosphate rock rapidly increased from \$80/tonne in November 2007 to peak at \$430/tonne in August 2008 (World Bank, 2014), a 400% increase that is clearly shown in Figure 16. This price spike, which was completely unforeseen by World Bank commodity price forecasts (World Bank, 2007), followed an increase in the price of many commodities at the time, including oil, but was exacerbated by a series of events where demand quickly exceeded supply for phosphate rock. The main drivers for increasing demand were to increase food production, especially as food commodity prices were also increasing at this time, and to grow more biofuels in response to government subsidies around the world. The supply market was already tight at this point, with low stocks and a low capacity to quickly increase production to keep up with demand, generating a short term 'lag' in phosphorus supply. The global supply situation was then made worse when China, the world's largest phosphate rock producer, imposed a 135% export tariff on phosphorus to effectively stop exports and protect domestic supplies (Elser and White, 2010).

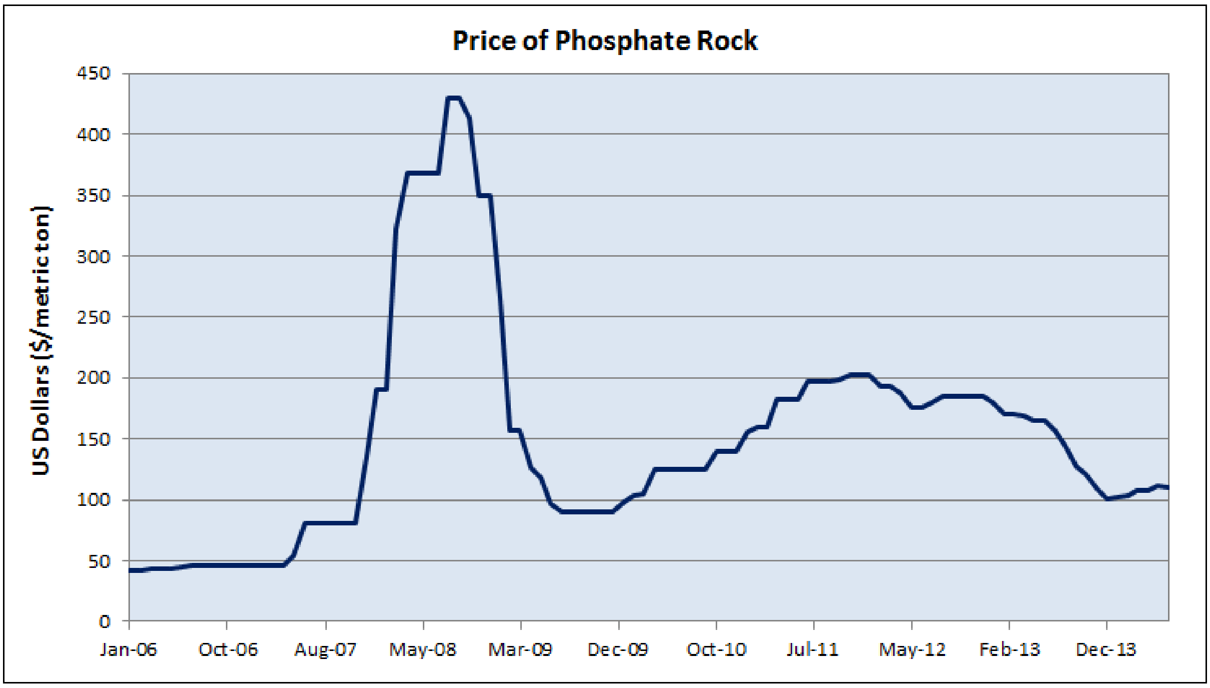


Figure 16: Price of Phosphate Rock.
Data source: World Bank (2014).

As can be seen in Figure 16, the price rapidly decreased during 2008/09 as supply increased and demand decreased, although the price did not return to its original level before the price spike. The price of phosphate rock is currently (June 2014) around $110/tonne (World Bank, 2014). The increasing world production capacity (see Section 4.3.3) is likely to exceed increases in global demand (see Section 4.3.5), therefore the price of phosphate rock is expected to remain relatively constant or even decrease in the short-term. This trend is shown in Figure 16. However, longer-term indicators, such as population growth, changing dietary preferences and increased demand for non-food crops, suggest that the demand will continue to increase (see Section 4.3.5), while the supply becomes more concentrated and less resilient (see Section 4.3.4). Also, as discussed in Section 4.3.3, the cost of producing phosphate rock is also expected to increase as lower-cost deposits are depleted and producers have to mine lower grade ores (Figure 12) in increasingly difficult locations with increased energy costs, opening new mines and employing more expensive technology (Van Kauwenbergh, 2010). Therefore, the combined effect is that the price of phosphorus is likely to rise over the medium and longer term. The less diverse production system will also become more susceptible to price volatility, which will affect farmers around the world, including those in the UK or supplying food to the UK.

4.3.8 Analysis of key drivers

Table 10 below details the principal drivers that have the potential to create global scarcity and which pose a significant risk for the UK. This includes an evaluation of the timeframes within which these key drivers of scarcity would be expected to take effect. The timeframe estimates are purposely broad to reflect the ‘messy’ nature of the phosphate rock situation, which includes a lack of reliable information and a large degree of uncertainty surrounding phosphate rock reserves and future production. However, the proposed timeframes allow comparisons to be made as to which drivers of scarcity are more imminent, and it is suggested that price rises, price volatility and geopolitical causes of scarcity are more pressing concerns than complete depletion of reserves or a peak in production.

Table 10: The principal drivers of future phosphorus scarcity

Driver	Description	Sources of information / Explanation	Timeframe
Absolute Physical Scarcity	The point at which phosphate rock reserves are completely depleted.	• USGS 2013 R/P ratio = 324 years • USGS 2013 resource / production ratio = • Assuming increasing production of 1% to 2050, and 0% from 2100, lifetime of reserves = 230 years. • Assuming only 50% of Moroccan reserves are, or will become, true economic reserves, R/P ratio = 200 years.	>200 years
Peak Phosphorus	A peak in production in phosphate rock where demand exceeds supply	• Cordell et al. (2009) peak P estimate based on USGS 2008 reserve estimates = 2033. • Cordell et al. (2011) peak P estimate based on IFDC reserve estimate between 2051 and 2092 (mean = 2070). • IFDC report - “no indication that a peak phosphorus event” will occur in the next 20-25 years. • Mew (2011) – production won’t reach the levels required to cause a peak this century, instead a demand-side “plateau phosphorus” will be reached that could stretch for 168 years.	>50 years
Price rises / price spike	A rise in the price of phosphate rock that would impact the UK food production system.	• USGS 2012 – World production capacity is rapidly increasing, with Morocco doubling its capacity by 2017. Therefore, prices are expected to remain low in the short term. 5-10 years. • Longer-term indicators suggest prices will rise. 10+ years. • Rising energy costs, including the possibility of peak oil, could push up production costs for phosphate rock and fertilisers. <10 years • A further imbalance between supply and demand could cause another price spike. Unknown.	<50 years.

Geopolitical issues / supply disruptions	Security of supply issues generated through the geopolitical situation, such as price manipulation, conflicts, etc.	• Jasinski (2013) - China and the US will deplete their current reserves within 50 years at current production rates. As this is happening, production will either shift to other countries, mainly Morocco, or there will be a production deficit and scarcity. < 50 years. • Cooper et al. (2011) - Morocco will control an increasing share of production and will be able to control market prices. < 10 years • Conflicts over remaining resources would affect global supply. Unknown. • Disruption to Morocco's production through natural disaster, terrorist attack, regional instability etc. Unknown timing.	< 50 years.

4.3.9 Knowledge gaps

The literature review revealed that there is a great deal of uncertainty surrounding the size, distribution, quality and accessibility of phosphate rock reserves and resources. Understanding the size of such a critical resource is important to ensure that it is managed sustainability in the future. However, this assessment was beyond the scope of this thesis.

Most research to date relating to phosphorus scarcity has considered the reserves and production on a global basis. However, global reserves are made up of individual deposits within individual countries, and, as shown in Table 8, some countries are depleting their reserves faster than others. This could intensify phosphorus supply issues in the future. The intensifying geopolitical situation and the challenges of replacing depleted production were missing from the debate around phosphorus scarcity. Hence, the knowledge gap identified was how the relationship between reserves and production within individual countries (the R/P ratio) could influence the phosphorus supply landscape throughout the 21st Century and affect phosphorus security in the UK. This analysis was developed as part of this research, and the methodology is outlined in Section 5.3. The results are included in Section 6.3 and discussed in Section 7.3.

4.4 Resource management strategies

Guiding question: What strategy could be developed to encourage the UK water industry to manage phosphorus as a resource, and how would the industry respond to such as strategy?

The previous sections have revealed that there are sufficient quantities of phosphorus within wastewater to make an impact on phosphorus security in the UK, and that the methods and technologies exist to increase the amount of phosphorus that is removed, recovered and recycled from wastewater. However, as revealed in Section 4.1.2, the current legislation relating to phosphorus is almost entirely based on addressing phosphorus as a pollutant, rather than or including addressing phosphorus as a resource. Section 4.1.2.4 revealed that phosphorus recycling objectives may be introduced through a European Directive in the future, although there are currently no recycling requirements and no phosphorus recycling strategy in the UK.

The purpose of this final section of the literature review is to critically review resource management strategies that have previously been used to manage phosphorus in other countries, and other resources such as oil and renewable energy in the UK. This supports the overall aim of the thesis by establishing if increased phosphorus recycling from wastewater will be required as part of a resource management strategy. This review will identify aspects from other resource management strategies that are relevant to phosphorus management in the UK water industry. The final sub-section then considers how targets for resource management are normally set, in order to determine how recycling targets may be imposed on the water industry.

4.4.1 Managing oil resources

Oil is perhaps the most similar resource to phosphate rock as it is a critical, finite and non-renewable resource, with reserves that are largely controlled by just a few countries (non-homogenous) and are rapidly being depleted, and the potential to cause environmental damage from its use if the emissions are not captured. Therefore, the lessons learnt in managing oil could be applicable for managing phosphate rock.

There are several reasons why the UK may need to manage oil reserves. Unlike phosphate rock, the UK has some oil reserves, found in the North Sea, although production peaked in 1999, at around 137 Mt/yr, and has been declining since to around 45 Mt in 2012 (BP, 2013). Imports of crude oil have increased from 45 Mt in 1999 to 60.5 Mt in 2012 (DECC, 2013a). The UK is therefore becoming increasingly reliant on imports. It is estimated that the UK could be importing nearly 50% of its oil and over 55% of its gas by 2020 (HM Government, 2011). Furthermore, the use of oil and other fossil fuels contributes to greenhouse gas (GHG) emissions, and the UK government has committed itself to a legally-binding target of reducing emissions by 80% compared to 1990 levels (Climate Change Act 2008). Therefore, there is a need to reduce consumption of oil and other fossil fuels. As highlighted in the Carbon Plan, moving towards a more efficient, low carbon economy will also reduce the UK's reliance on imports and exposure to future price volatility, while developing industries with a long-term comparative advantage for the future (HM Government, 2011).

4.4.1.1 Renewable Energy Strategy

As a source of energy, oil can theoretically be substituted with other forms of energy, including other fossil fuels, nuclear and renewable energy. Since phosphate rock is the only primary source of phosphorus entering the market, the only applicable substitution method is with renewable sources. Therefore, this section will review the methods used to increase renewable energy production in the UK in order to identify measures that could be transferrable to a phosphorus management strategy.

The EU Renewable Energy Directive (2009/28/EC) establishes an EU-wide target of producing 20% renewable energy by 2020 (The European Parliament and the Council of the European Union, 2009). This has the dual objective of reducing greenhouse gas emissions and increasing security of supply (House of Lords, 2008). Member states were assigned renewable energy targets based on their starting point, the energy mix, and the renewable energy potential of a given country. The UK was given a target of generating 15% renewable energy by 2020 (The European Parliament and the Council of the European Union, 2009). Achieving this target requires incentivising or regulating the privatised UK energy industry to invest in renewable energy production. This has many parallels with achieving a phosphorus recycling target within the privatised water industry.

The Renewable Energy Directive states that Member States should establish national renewable energy action plans. The UK Renewable Energy Strategy was published in July 2009, and sets out how the UK will meet the legally-binding target of 15% renewable energy by 2020 (HM Government, 2009b). This Strategy includes putting in place mechanisms that provide financial support for renewable energy.

The Renewables Obligation (RO) is the main mechanism being used to support the large-scale deployment of renewable electricity in the UK (Ofgem, 2014). The UK Renewable Energy Strategy includes a commitment to expand and extend the RO to ensure that it delivers 30% renewable electricity by 2020 (HM Government, 2009b). Similar schemes have been used to support renewable energy generation in Spain and the Netherlands (DECC, 2009).

The RO Orders place an obligation on electricity suppliers to source an increasing proportion of their electricity supply from renewable sources (Ofgem, 2014). This is set annually by the Department of Energy and Climate Change (DECC) as a number of Renewables Obligation Certificates (ROCs) that must be presented per MWh of electricity supplied. In 2012-13, licensed suppliers had to present 15.8 ROCs per 100 MWh of electricity supplied (Ofgem, 2014). The energy suppliers are able to fulfil their obligations by either purchasing ROCs from licensed generators, paying a buy-out fee, or a combination of the two (Ofgem, 2014). The buy-out fees set a cap on the maximum price of the traded certificates (Toke, 2008). Renewable energy generators receive additional income from selling both the electricity and ROCs. The buy-out fees are redistributed to suppliers in proportion to the number of ROCs they present, which further increases the value of the ROCs.

Initially, one ROC was given to each MWh of electricity produced from renewable sources. However, in April 2009 a banding system was introduced to encourage investment in a more diverse range of generating technologies (DECC, 2009). For example, offshore wind now typically receives 2 ROCs per MWh, whereas onshore wind receives just 1 ROC per MWh (Ofgem, 2014). The introduction of banding also means that one ROC no longer represents one MWh of renewable generation (Ofgem, 2012). For example, in 2008-09 before banding was introduced, 19.0 TWh of renewable electricity were generated and 19.0 million ROCs were issued, whereas in 2010-11, 23.2 TWh were generated and 24.9 million ROCs were issued (Ofgem, 2012).

In April 2009, the ‘headroom’ approach was introduced. Headroom sets the obligation level at a set percentage (currently 8%) above the number of ROCs that are expected to be issued in a given year (DECC, 2009). The goal is to not restrict the growth of the renewable electricity industry, but instead allow the level of deployment to grow above the trajectory level. Also, headroom ensures that obligation levels stay sufficiently ahead of deployment to avoid a crash in ROC prices that would result from supply of ROCs reaching or exceeding the obligation level (DECC, 2009).

The RO was extended in April 2010, and will now run until 2017 (Ofgem, 2012). The RO will continue to function as the primary support scheme for large-scale renewable electricity projects to help meet the UK’s Renewable Energy targets (DECC, 2009). This extension means that renewable energy projects built right up to 2020 will receive 20 years of RO support to ensure they are economically viable (DECC, 2009).

Compared to the other main mechanism for supporting renewable energy (a feed-in tariff) there are several advantages to the RO scheme. The main benefits are that objectives are defined and achieved, while the industry is allowed to choose where to invest the money most cost-effectively (Hislop and Hill, 2011). Eurelectric, which represents the majority of transnational electricity companies, argued that trading certificates can reduce the cost of meeting ambitious renewable energy targets since technologies can be implemented where it is most cost-effective to do so (Toke, 2008). However, in the debate about creating a trading scheme for renewable energy between EU member states, the European Renewable Energy Council (EREC) demanded that trading should only be permitted to countries that have fulfilled their targets (Toke, 2008).

There are also several criticisms of the RO scheme. One of the primary criticisms of the trading scheme is the unstable price of certificates and the unstable income for renewable energy generators. This uncertainty ultimately raises the costs of financing projects. The unstable revenue generated under the RO provides excessive profits when the electricity prices are high, but makes projects uneconomical when electricity prices are low (DECC, 2009). The issues with unstable prices generated in a cap and trade scheme was raised as an issue in the EU Emissions Trading Scheme (EU ETS) where the value of emissions permits fluctuated widely in price. To counter this, the government introduced the Carbon Price Floor (CPF) in 2013, which is effectively a carbon tax to support a more stable carbon price (HM Government, 2011). Also, when comparing the certificate trading schemes to a feed-in tariff system, historic observations for EU member states suggests that feed-in tariffs have resulted in greater renewable energy development, and at lower cost for consumers than trading schemes (Toke, 2008).

As part of the Electricity Market Reform (EMF), the RO is being replaced by the Contracts for Difference (CfD) scheme. The CfD scheme started in 2014 and will run in parallel to the RO until the RO is closed for new generation in 2017 (DECC, 2013b). The CfDs will provide support for low carbon generation, including nuclear, renewables and carbon capture and storage (CCS), as the government focusses on reducing emissions from the energy sector. This change was proposed to overcome issues of unstable revenue generated under the RO (DECC, 2009). The CfDs support low carbon generation by paying the difference between the market price and investment cost (the strike price) when the market price is low, but then making the generators pay money back if the market price rises above the strike price (DECC, 2013b). This provides a stable income for generators, and ensures that they do not receive unnecessary support when the market price is high (DECC, 2013b).

4.4.2 Phosphorus management in other countries

Despite a lack of European legislation, several countries have pursued with national programs for phosphorus management. The benefits of introducing national recycling targets include increased phosphorus security, reduced vulnerability to price spikes, and the creation of jobs and industries that will become more valuable in the future as phosphorus recycling increases across Europe. This section looks at these initiatives to determine how this is being implemented and identify measures that could be transferrable to phosphorus recycling in the UK.

The Swedish Environmental Protection Agency published a report in 2012 which included a survey of phosphorus resources, an assessment of the potential for phosphorus recycling, and a proposal for statutory requirements with a milestone target of recycling at least 40% of phosphorus and 10% of N from waste by 2018 (Swedish Environmental Protection Agency, 2013). Sweden has also introduced a national target of recycling 60% of phosphorus from wastewater by 2015, with at least half recycled to arable land (Fischer et al., 2012). Germany is planning similar legislation to Sweden (CIWEM, 2012). In Switzerland, the new sludge strategy of Canton Zurich centres on phosphorus recovery from mono-incineration ash, with a target of recycling 80% of total phosphorus (ESPP, 2013b), and the revision of the Swiss federal ordinance on waste treatment, due to be published at the end of 2015, includes an obligation to recover phosphorus from sewage sludge and animal meat and bone meal (ESPP, 2014). Finally, Denmark has published a strategy on resource use, which recognises phosphorus as a critical resource and sets phosphorus recycling as a national objective, with the target of recycling 80% of phosphorus from municipal sewage (ESPP, 2013c).

In a Policy Position Statement on phosphorus, the Chartered Institution of Water and Environmental Management (CIWEM) stated that action is required now to reduce the rate of phosphorus depletion, and high priority should be given to recovering phosphorus from urban wastewater (CIWEM, 2012). However, there is currently no legislation or strategy for managing phosphorus in the UK.

4.4.3 Setting a target

An effective strategy requires targets to be set. These targets provide clarity and stability to the industry, and therefore they must be clear, specific and mandatory in order to be effective (EC, 2007). The importance of defining specific targets is stressed within the Europe 2020 Strategy (EC, 2010b).

The targets can be proportional or absolute targets. These can be very different, so a clear differentiation is required. For example, the Millennium Development Goal (MDG) 1 and the 1996 World Food Summit (WFS) targets appear very similar: to halve the number of people who suffer from hunger between 1990 and 2015. However, MDG1 refers to halving the proportion of people suffering from hunger by 2015, which could still be achieved having decreased from 23% in 1990-92 to 15% in 2010-12 (UN, 2013a), whereas the 1996 WFS target refers to halving the total number of people suffering from hunger by 2015, which will not be achieved by 2015 since the number of people suffering from hunger remains virtually unchanged at around 840 million people (FAO, 2013, FAO, 1999).

The target must be specific, and longer-term targets are usually rounded to the nearest 10%. For example, the climate change act establishes the target of reducing emissions by 80% by 2050 (Climate Change Act 2008). Also, the EU has established the target of reducing GHG emissions by 20% by 2020 and increasing renewable energy by 20% by 2020 (The European Parliament and the Council of the European Union, 2009). This 20 20 by 2020 package was criticised for being more of a slogan, rather than an empirically based target, and the European Commission agreed that, although grounded in scientific study, the 20% target was not completely arrived at through deep scientific reasoning (House of Lords, 2008).

Targets must also include a specific deadline for their achievement. The timeframe for achievement has to be far enough into the future to allow significant changes to occur, but not so far as they become irrelevant and do not require action to be taken now. The UK climate change targets are to reduce emissions by 34% by 2020 and by 80% by 2050 (Foresight, 2011). The Roadmap to a Resource Efficient Europe sets a vision for 2050, which includes sustainable management of all resources, and then 2020 milestones to make recycling more economically attractive and develop markets for secondary materials (EC, 2011).

Effective strategies require a baseline performance to be determined. This baseline allows realistic targets to be developed and performance to be measured. For example, climate change targets and Millennium Development Goals' targets are compared to the 1990 baseline level.

The path taken from the baseline position to the end point is not necessarily a linear path. There may be advantages in taking more action earlier on to improve security of supply and establish competitive industries. Alternatively, waiting to take more action later on may enable time for certain technologies to mature which are able to deliver the targets for less cost. The GHG emissions path taken to meet the UK's climate change targets is determined through the use of Carbon Budgets. These are legally-binding emissions targets set over successive 5-year periods (CCC, 2008). The budgets are set for the three periods ahead, so it is clear to investors what the targets will be for the next 15 years. As outlined in The Carbon Plan, the focus initially will be to target the 'easy wins' which are the most cost-effective measures that are most easily implemented (HM Government, 2011). The 'early action' pathway was revealed in the fourth carbon budget impact assessment as being more likely to be cost effective, compared to pathways with greater levels of emissions reductions later on (DECC, 2011a).The Committee on Climate Change (CCC), which is an expert, independent statutory body, was set up to recommend what level these carbon budgets should be, and then monitor actual progress over time (CCC, 2008). As more information and analysis develops over time, the end target and carbon budgets can be adjusted accordingly.

4.4.4 Knowledge gaps

Although several countries have now introduced national phosphorus recycling targets, there is little information available about how these targets will be achieved and how individual water companies will be encouraged or managed to increase the amount of phosphorus that is being recycled.

Critical resources, such as oil, are being managed to increase the sustainability of future energy supplies, and reduce security of supply risks. A key component of this involves the development of renewable energy sources. There are many similarities between renewable energy and renewable phosphorus, which suggests that the strategies being employed to increase the production of renewable energy could be adopted to increase the production of renewable phosphorus within the UK water industry. However, there is currently a lack of understanding of how a renewable phosphorus strategy would function in the UK water industry, and whether this could shift phosphorus management practices to increase recycling from wastewater. Therefore, a Phosphorus Recycling Obligation (PRO) scheme was developed for this research. The methodology used for testing how the PRO scheme would function to achieve specific phosphorus recycling targets is outlined in Section 5.4. The results are presented in Section 6.4, and the discussion is included in Section 7.4.

It is clear that targets must be set to achieve the desired result. A number of countries have established national-scale phosphorus recycling targets, including contributions from the wastewater industries. However, no analysis of what targets would be appropriate for the UK water industry were identified in the literature review. This includes an assessment of the feasibility of reaching such targets, which water companies would contribute most to meeting these targets and how this could improve phosphorus security for the UK by reducing the reliance on imported phosphorus. This will be investigated further in conjunction with testing a renewable phosphorus strategy.

5 METHODOLOGY

In order to determine if the UK water industry will be required to increase the amount of phosphorus that is recycled from wastewater in the future, additional analyses were required to address the knowledge gaps identified in the literature review. This section presents the methods developed for these analyses, which includes:

- Evaluating the current position of the UK water industry
- Developing a substance flow analysis of phosphorus in the UK
- Assessing a key driver for global phosphorus scarcity
- Testing a resource management strategy for phosphorus in the UK water industry.

5.1 Evaluating the current position of the UK water industry

The literature review (Section 4.1) revealed that the UK water industry currently manages phosphorus almost entirely as a pollutant. There are currently no legislative drivers in the UK to recover and recycle phosphorus from wastewater. Very little information was available about the existing infrastructure of the UK water industry, including the exact number of WwTWs operated by each water company, and the size and treatment methods employed at each of the WwTWs. This information was required to determine if phosphorus recycling within the water industry could be increased and what contributions could be made from the different water companies. Therefore, the intention was to gather and critically analyse this information. In particular, the information required was:

- A dataset of all WwTWs in the UK, including the name and size (population equivalent (p.e.)).
- Phosphorus flows through each WwTWs.
- The method of secondary treatment.
- A dataset of the WwTWs that require phosphorus removal and the phosphorus consents applied at these works.
- The method of phosphorus removal employed (e.g. chemical or biological phosphorus removal).

Most of this information was available from all 12 UK water and wastewater companies, held in company databases. The information gathered was compiled into a complete dataset for all WwTWs in the UK water industry. However, the phosphorus flows to WwTWs are rarely measured, particularly for smaller works without phosphorus consents, and this information was largely unavailable. Therefore, a number of assumptions were required:

- The total amount of phosphorus within wastewater received by WwTWs is 55 kt P/yr. This figure is greater than the 48.4 kt P/year estimated by UKWIR (2010) (See Section 4.1.6), and was revised to be consistent with the water industry flows identified from the results of the UK SFA (Section 6.2.6).
- The amount of phosphorus received at a single WwTWs is proportional to the size of that works (as p.e.). For example, a WwTWs serving 10% of the UK population (as p.e.), would therefore receive 5.5 kt P/yr within wastewater.

A primary goal of the study was to identify the phosphorus flows within the water industry, so that the phosphorus loads to individual water companies and individual WwTWs could be calculated. The secondary goal of the data collection was to determine if the existing wastewater infrastructure is compatible with existing phosphorus recovery technologies, which is outlined in Section 5.1.1. Furthermore, the data collected was fundamental for the development and testing of phosphorus recycling obligation scheme (Section 5.4).

The data was collected between August 2012 and July 2013, and it is assumed that the data received by the companies during that period represented their most up-to-date information. However, it must be noted that the existing wastewater infrastructure will change over time through additional investment to increase treatment capacity and efficiency, whilst complying with legislation and meeting environmental performance targets, which is likely to include increased phosphorus removal.

5.1.1 Determining the potential for phosphorus recovery at UK wastewater treatment works

The literature review revealed that, despite there being many phosphorus recovery technologies in development or operating at full-scale, there is currently only one installation in the UK, and this is producing a relatively small amount of fertiliser compared to the other phosphorus flows in the water industry and throughout UK food production system. No analysis was identified in the literature of the potential for phosphorus recovery technologies based on existing UK wastewater infrastructure. Therefore, the purpose of this study is to match the requirements of phosphorus recovery technologies with the existing infrastructure of the UK water industry. This will reveal the current potential for phosphorus recovery, as well as the changes that would be required to increase this potential.

As identified in Section 4.1.5, recovery of struvite is considered as the most promising form of phosphorus recovery. Therefore, the potential for phosphorus recovery will focus primarily on struvite recovery. There are several technologies available to recover struvite from wastewater, although the Ostara Pearl Process has been proven at several full-scale installations and is also the only form of phosphorus recovery to be in operation within the UK, installed in 2013 at Slough WwTWs. Therefore, the potential for struvite recovery will be based upon the requirements for Ostara's struvite recovery process. According to Britton (Britton, 2009), these requirements are for a WwTWs that is:

- >20 million litres per day. Assuming that each person uses 150 l/day (Water UK, 2006b), translates into works >130,000 p.e.
- Operating activated sludge (AS) processes.
- Operating enhanced biological phosphorus removal (EBPR) processes.
- Operating with minimal chemical addition for phosphorus removal.

These requirements were compared to the size, secondary treatment type and method of phosphorus removal of UK WwTWs. As identified in Section 5.1, this information was gathered from all 12 UK water companies as part of this thesis, and is presented in Section 6.1. The phosphorus loads to suitable WwTWs were estimated following the assumptions outlined in Section 5.1, and the total recovery potential for struvite was estimated at 40% of the phosphorus load to the WwTWs (Petzet and Cornel, 2011).

5.2 Developing a substance flow analysis of phosphorus in the UK

A country-scale substance flow analysis is considered a vital step in creating a national resource management system. However, the literature review (Section 4.2.1) revealed that although there is a growing number of national-scale SFAs for phosphorus, there was no complete SFA for phosphorus in the UK. Therefore, the aim was to develop a country-scale SFA in order to determine the UK's current reliance on imported phosphorus, to identify areas of inefficient use and, primarily, to quantify phosphorus flows to the UK water industry and compare this to other major flows within the UK system. This would reveal if the water industry is a key stakeholder in UK phosphorus management, and therefore if the industry would be required to increase phosphorus recycling in the future to address resource security.

5.2.1 Defining the system boundaries

Conducting a SFA follows a set procedure. The underlying principle of a SFA is the conservation of mass, where a material can be transformed but not lost (Graedel and Allenby, 2010). Phosphorus may move within flows and between stocks, being transformed into different chemical forms or accumulating within stocks, but never being destroyed. Therefore, all flows into a system must either accumulate within or flow out of that system, and the equation must balance.

The first step is to define the system boundaries, which are both geographical and temporal. The geographical system boundary for this SFA is the UK, which includes England, Scotland, Wales and Northern Ireland. The phosphorus flows into, out of, and throughout the UK will be analysed, focussing primarily on agriculture and the food production system since agriculture accounts for more than 90% of all phosphorus applications (Brunner, 2010), but also including other industrial applications that interact with this system, such as phosphorus in detergents which may be removed from wastewaters and applied to agricultural land within sewage sludge.

It is common practice for SFAs to calculate flows over an entire year. As identified in Section 4.2.1, some SFA studies have analysed flows over a number of years to reduce annual variations and monitor changes over time, while others focus on a single year. For the purpose of this study, which was to quantify phosphorus flows in the water industry in comparison to other major flows in the UK, it was decided that it would be appropriate to study flows for a single year. Therefore, the temporal system boundary chosen for this SFA was the year 2009, which was chosen as it represented the most recent year for which an almost complete dataset could be gathered at the time of writing (2011/12). However, it should be noted that annual variations can be significant.

5.2.2 Obtaining data

The SFA requires the flows and stocks of a system to be identified, and then sufficient data to be gathered to quantify them. Primary data collection through surveys or specific analyses was not required to complete this SFA for the UK. Instead, the data was gathered from secondary sources using three principal methods. Firstly, as detailed in Section 4.2.2, a literature review was undertaken to identify existing studies that contained information relating to phosphorus flows in the UK. Several studies were identified which contained useful information, for example phosphorus inputs and soil balances in agriculture (Withers et al., 2001, Clothier, 2010), and phosphorus flows through UK WwTWs (UKWIR, 2010) and to water bodies (White and Hammond, 2006). Some of the estimates from these studies needed to be scaled up to the UK scale, and the methods and assumptions used to achieve this are outlined in Table 25. Secondly, data was obtained from national statistics for the quantities of materials such as agricultural crops, imported food and food waste. Average phosphorus concentrations were then applied to these materials to calculate the weight of phosphorus. And finally, the mass balance principal was applied where possible to obtain additional estimates for individual stocks and flows. For example, if phosphorus additions and removal to the soil could be calculated from national statistics, then a mass balance could be used to determine the accumulation of phosphorus in the soil. Using these three methods, a number of estimates were produced for most flows and stocks.

The approach was designed to be as transparent as possible. Therefore all of the assumptions and calculations, average results and uncertainty ranges are presented in Table 25.

5.2.3 Presenting the results

As highlighted in Section 4.2.1.3, the visual presentation of a SFA can be challenging since there are a large number of flows and stocks. No standardised layout has been agreed upon, despite many authors recognising the usefulness of a standard model in allowing easier comparisons between countries. The model used in this study adopted a layout similar to the one produced by Senthilkumar et al. (2012) for the SFA of phosphorus in France. The program STAN (www.stan2web.net) was used to present the results (Figure 21). The boxes represent the main processes and stocks, while the connecting arrows represent the main flows. The flows are presented in the Sankey format, with the width of the arrow being proportional to the size of each flow.

The SFA follows the element phosphorus throughout the system, no matter what form it is in, therefore all flows were converted to quantities of elemental P. As identified in Section 4.2.1.2, the unit for quantity varies between other national-scale SFA studies. In this study, phosphorus flows will be expressed in thousand tonnes of phosphorus per year (kt P/yr), and stocks as thousand tonnes of phosphorus (kt P).

5.2.4 Reducing and estimating uncertainty

There are several methods of dealing with and reducing uncertainty, as outlined in Section 4.2.1.4. The SFA conducted for this study employed cross-checking of results through the use of alternative calculations, comparing calculated estimates to values obtained from the literature, and deriving mass balance estimates where possible. This enabled most of the data points to have at least two estimates derived from different methods of calculation. This approach was useful to confirm the results and avoid calculation errors by highlighting erroneous results.

There were a few instances where double counting could have occurred, for example imported crops could have been counted twice in crops and also in imported animal feed. To avoid this, commodities with a potential risk of double counting were first identified, the use for each commodity was then determined and categorised into a single flow, ensuring that it was removed from other flows.

The various estimates for each data point were used to produce average values for each flow. The standard deviation has been employed to show the spread of results used to obtain this average value. Two standard deviations correspond to 95% confidence limits that the true value lays within that range. However, such statistical methods are less suited to the small number of data points obtained in SFA studies. For results with only one method of calculation, this method produces no uncertainty range, while producing incredibly small ranges for two very similar results.

An alternative method of producing a confidence range for SFA studies was developed by Hedbrant and Sörme (2001), and is referred to as the HS model. This method involves assigning uncertainty levels to various data sources, such as official statistics or values from literature, and applying an interval to each level. The uncertainty intervals used are detailed in Table 11.

.

Table 11: Uncertainty intervals

Level	Interval (multiply or divide)	Source of Information	Example
1	*/ 1.05	Official Statistics at UK scale.	UK population estimate.
2	*/ 1.1	Official Statistics at UK scale. Value from literature.	Area of land, crop yields, animal numbers from Defra or BSFP. phosphorus contents from literature.
3	*/ 1.2	Official statistics scaled up to UK scale. Values from literature.	Sludge production scaled up to UK scale. Animal numbers scaled up from Britain to UK. Specific values from other studies in literature.
4	*/ 1.33	Values from literature without reference or methodology. Significantly scaled results or other assumptions.	Quoted values or own assumptions of phosphorus content. Housed manure scaled up to total manure, then to UK scale. Assumptions about waste disposal or use of animal wastes.

When using the HS model, an issue arises when a range of calculations are used to produce estimates for the same data point. To overcome this, a confidence interval was developed for each separate calculation using the methodology and equations outlined in Antikainen et al. (2005), and then an average confidence interval was taken for the overall data point. These average interval values are presented in Table 25. To balance the SFA model and allow an easier comparison between the two uncertainty methods results, it was necessary to convert the */ range into a +/- range. This was achieved for example by converting an interval of */1.1 into +/- 10%, which gives an equivalent upper limit but extends the lower limit.

The largest range produced by the two methods of estimating uncertainty (standard deviation and HS model) was entered in the STAN SFA program for each data point and used within the balancing application to validate the model and produce the final results. The final results are then presented with the 95% confidence limits.

5.3 Assessing a key driver for global phosphorus scarcity

The literature review involved a critical analysis of the key drivers of global phosphorus scarcity in order to determine when phosphorus scarcity could become an issue in the UK, and to establish a timeframe for when increased phosphorus recycling within the wastewater will be driven by the need to increase UK phosphorus security. As shown in Table 10, Section 4.3.8, the geopolitical and economic risks, as opposed to the physical risks, present the most pressing security of supply concerns. The analysis suggests that the intense geopolitical situation surrounding phosphate rock reserves could lead to reduced availability and additional price spikes in the short term (<50 years).

The literature review revealed that most assessments of phosphorus scarcity consider reserves and production on a global basis. However, global reserves are made up of individual deposits within individual countries, and these individual countries are depleting their reserves at different rates, as shown by the reserve to production (R/P) ratios in Table 8, Section 4.3.4. This means that the current geopolitical situation will change in the future and could intensify the security of supply issues. This research was intended to address this knowledge gap and determine how the relationship between reserves and production within individual countries could influence the phosphorus supply landscape throughout the 21st Century. The results from the analysis could then be used to establish if the water industry will be required to increase phosphorus recycling from wastewater within relevant timeframes.

The analysis required three scenarios to be developed and some simplifying assumptions to be applied. USGS 2011 phosphate rock reserve estimates were obtained from Jasinski (2011), which estimated global reserves at 65,000 Mt. This estimate was assumed to be accurate, despite the uncertainty surrounding this estimate, which is discussed in Section 4.3.1. It was also assumed that the size of phosphate rock reserves would only change throughout the analysis period as a result of extraction. Therefore no allowance was made for new discoveries or reclassifications of resources to reserves. Anticipating such events would be “living beyond our means” (Vaccari and Strigul, 2011), and was therefore avoided.

The first scenario was developed to determine how the depletion of reserves in certain countries would affect global production in the future, up to the year 2100. Current production estimates for individual countries were obtained from USGS 2011 estimates, and it was assumed that individual countries will continue to extract their reserves at a constant rate until the entire reserve is depleted, at which point production will cease. In reality, it is expected that production will be phased out as the mine draws closer to depletion.

The second scenario was developed to compare the decreasing supply from the first scenario with the anticipated increase in global demand for phosphate rock (see Section

4.3.5) in order to identify the size of a potential production deficit in the future. It was assumed that the demand for phosphate rock will increase by 1% per year between 2010 and 2050, resulting in a global phosphate rock production requirement of approximately 260 Mt in 2050, which is consistent with estimates from other analyses as shown in Table 9, Section 4.3.5. It was also assumed that the demand for phosphate rock will stabilise (0% growth) between 2050 and 2100 at 260 Mt per year. This plateau is predicted by several analysts as discussed in Section 4.3.5, and is linked to the slowdown in population growth expected during the second half of the century, but could be an underestimate as other factors will also influence future demand.

The final scenario was developed to determine how increasing production within certain countries to accommodate the production deficit identified in the second scenario would affect the distribution of phosphate rock reserves and share of production in the future. It was assumed that production within individual countries will increases in proportion to the size of the reserves held by that country. For example, if global production needed to be increased by 10 Mt, then a country with 20% of the global reserves at that time would increase production by 2 Mt. To simplify the analysis, it was assumed that production within individual countries can continue to increase until the entire reserve is depleted, at which production would stop. However, in practice it is expected that extraction will follow a declining production curve and reduce as the deposit nears depletion.

The results from this analysis were assessed to determine how this could shape the future distribution of reserves and share of global production, and how this would impact UK phosphorus security. The results are presented in Section 6.3, and formed the basis of the paper produced by Cooper et al. (2011), which is included in Appendix A.

5.4 Testing a resource management strategy for phosphorus

The literature review revealed that a number of countries have established national-scale phosphorus recycling targets, which includes contributions from the wastewater industries. However, there was very little information about how these targets will be achieved and how individual water companies will be encouraged to increase the amount of phosphorus that is recycled. No such targets currently exist within the UK for phosphorus, although other critical resources, such as oil, are being managed to increase the sustainability and security of supplies, which includes the development of renewable energy alternatives.

A Renewable Phosphorus Strategy in the UK would have many similar features to the UK Renewable Energy Strategy. For example, the goal of the Renewable Energy Strategy is to increase the amount of renewable energy produced in the UK. This will increase energy security for the UK, create thousands of jobs, and help to address the environmental issue of climate change (HM Government, 2009b). Similarly, the goal of a phosphorus management strategy would be to increase the amount of ‘renewable’ phosphorus that is produced in the UK. This will increase phosphorus security for the UK agricultural industry, create jobs, and help to address the environmental issue of eutrophication. The UK energy and water industries are also very similar, with a small number of privately owned companies that have unique characteristics in terms of size and infrastructure, and must be regulated or incentivised to make decisions that produce desired outcomes for the whole industry. Furthermore, the technological options for producing both renewable energy and renewable phosphorus are diverse and rapidly growing, and it is expected that a range of solutions will be required to meet the overall targets.

Because of the similarities between renewable energy and renewable phosphorus, the aims of this analysis were to determine if a strategy similar to the UK's renewable energy strategy could be applied within the UK water industry to meet specific phosphorus recycling targets, what affect this would have on the individual water companies, and what impact this would have on national phosphorus security. If increasing phosphorus recycling from wastewater is too expensive, and the impact on national resource security is too small, then this would suggest that the industry would not be required to increase phosphorus recycling in the future.

This section establishes the assumptions of how the Renewable Phosphorus Strategy would function in the UK and how the water companies would respond to such a strategy. This involves the following steps:

1) Establishing the baseline position in terms of phosphorus flows
2) Developing appropriate recycling targets
3) Developing the renewable phosphorus strategy
4) Measuring the response by individual water companies

5.4.1 Establishing the baseline and performance indicators

Effective strategies require a baseline performance to be determined against which realistic targets can be set and performance can be measured. The baseline position for the industry was determined using the data gathered about existing infrastructure of the UK water companies (Section 6.1) and the substance flow analysis of phosphorus within the water industry (Section 6.2.6). The results from these analyses revealed that the total phosphorus flows through the industry in 2009 were approximately 55 kt P/yr (see Section 6.2.6), and that UK WwTWs in 2012 had a combined size of 71,264,836 p.e. (Section 6.1.1).

A number of performance indicators were developed to assess the changing performance of the industry as a whole over time, as well as the relative performance from individual water companies. The performance indicators are detailed below in Table 12.

Table 12: Performance indicators for phosphorus recycling

Performance parameter	Unit
1. Amount of P entering UK WwTWs	tonnes P/year
2. Amount of P in final effluent	tonnes P/year
3. P removal efficiency	%
4. Amount of P in sewage sludge recycled to agricultural and non-agricultural land[1].	tonnes P/year
5. Amount of P recovered from wastewater (e.g. struvite)	tonnes P/year
6. Amount of P recovered from thermal destruction processes[2].	tonnes P/year
7. Total amount of P recovered or recycled from wastewater	tonnes P/year
8. Percentage of P recycled from wastewater	%

Note:

1) Includes processed sewage sludge (dried, pelletised etc.) and any products recovered from sewage sludge. Non-agricultural land applications include uses for land reclamation, forestry, and non-food energy crops.
2) Includes all thermal destruction processes such as gasification, pyrolysis and super critical water oxidation.
3) 'Other' sludge disposal includes, amongst others, uses for land reclamation, forestry, and composting, as well as disposal to land fill and non-agricultural land.

5.4.2 Developing a phosphorus recycling target

As discussed in Section 4.1.2.4, there is no legislative requirement to recycle phosphorus from wastewater in the UK. However, as detailed in Section 4.4.2, some countries have introduced phosphorus recycling targets despite the lack of European legislation. For example, Sweden has a target of recycling 60% of phosphorus from wastewater by 2015 (Fischer et al., 2012), the sludge strategy of Canton Zurich, Switzerland, is aiming to recycle 80% of the total phosphorus (ESPP, 2013b), and Demark has introduced a target of recycling

80% of phosphorus from municipal sewage (ESPP, 2013c). CIWEM (2012) suggests that it would be feasible to recycle around 95% of the phosphorus from wastewater and recommends that all governments make phosphorus recycling a legal requirement. Conducting a detailed analysis of what phosphorus recycling target for the UK water industry would be most feasible and cost-effective was beyond the scope of this thesis. For this analysis, however, it was assumed that the target is to recycle 80% of all phosphorus within wastewater by 2050. This amount of phosphorus is consistent with targets set in other countries, and the timeframe chosen is supported by the analysis of drivers of global phosphorus scarcity (Section 4.3.8), which suggests that geopolitical factors could affect security of supply in the near term (<50 years).

As detailed in Section 4.4.3, to ensure the UK remains on track to meet its 2050 carbon emissions reduction target, a pathway of intermediate targets have been developed. These are five-yearly, legally binding carbon budgets which established for the following 15 years and determine when most action should be taken (HM Government, 2009a). The fourth carbon budget impact assessment determined that the ‘early action’ pathway is likely to be the most cost effective. Carbon budgets are based on modelling undertaken by the Climate Change Committee. However, there are no identified models which could be used to inform the phosphorus recycling pathway from the baseline position to the 2050 target, and developing such models was beyond the scope of this thesis. Therefore, for this analysis, a linear pathway was adopted. This linear pathway of equal annual percentage increases year on year does in fact act as an early action pathway, as it requires larger absolute changes in earlier years (DECC, 2011a). For example, increasing the amount of phosphorus recycling from 50% to 55% (i.e. 5 percentage points) involves increasing the absolute phosphorus recycling by 10%, whereas increasing the amount of phosphorus recycling from 75% to 80% (5 percentage points) involves increasing the absolute phosphorus recycling by 6.7%. Therefore, larger absolute changes are required in earlier years, and a linear pathway is actually an early action pathway. The intermediate targets are presented in Table 13.

The baseline year chosen was for 2009, which was the year for when data was gathered for the substance flow analysis, which included phosphorus flows through the industry. This revealed that the amount of phosphorus recycled from wastewater was approximately 41% (see Section 6.2.6). To achieve the overall target of 80% phosphorus recycling by 2050, a linear pathway would follow the intermediate targets established in Table 13. As discussed in Section 4.4.3, longer term targets are normally rounded up to the nearest five or ten. Therefore, the suggested phosphorus recycling targets have been slightly modified from the linear path to reflect this, as shown in Table 13. From 2015 to 2050, the proposed targets increase by 1% per year, from 45% in 2015 to 80% in 2050.

Table 13: Wastewater phosphorus recycling targets

Year	Recycling targets based on a linear increase	Proposed phosphorus recycling targets
2009	41%	41%
2012	44%	44%
2015	47%	45%
2020	51%	50%
2025	56%	55%
2030	61%	60%
2035	66%	65%
2040	70%	70%
2045	75%	75%
2050	80%	80%

5.4.3 The Phosphorus Recycling Obligation (PRO)

As identified in Section 4.4.1.1, the Renewables Obligation (RO) was chosen as the primary mechanism to increase renewable electricity generation in the UK. Based on the same principles as the RO, a Phosphorus Recycling Obligation (PRO) scheme was developed as part of this research to test how a specific phosphorus recycling target could be achieved within the UK water industry and how the individual water companies would respond and contribute to this target. This section outlines the key features of the PRO scheme.

The PRO scheme involves an industry-wide phosphorus recycling target to be set each year, which is consistent with the target pathway to 2050 (see Table 13). This target is expressed as a percentage of total inflow phosphorus, and for this analysis each individual water company was given the same percentage target. The amount of phosphorus that needed to be recycled in a given year was calculated for each company, and expressed as a target number of Phosphorus Recycling Obligation Certificates (PROCs) that must be submitted at the end of each year. The phosphorus inflow to water companies was estimated based on the size of the population served by WwTWs, as described in Section 5.4.1.

In this analysis, 1 kg phosphorus that is recycled would earn 1 PROC. Companies that do not meet their obligation must either buy PROCs from other companies, or pay a fixed buy-out fee at the end of the year for each certificate required. Companies that produce more PROCs than required can sell these to other companies, or receive a surplus fee at the end of the year. Surplus PROCs cannot be retained for future years. This trading mechanism between companies is designed to encourage the most cost-effective investments to be made so the industry reaches its target at least cost.

A criticism of the RO was that the price of ROCs can vary significantly. In fact, as discussed in Section 4.4.1.1, the RO is currently being replaced by the CfD scheme to reduce financial uncertainty and to shift the focus on reducing carbon emissions, rather than generating renewable electricity. The CfD scheme is feasible for electricity generation since the range of generation technologies essentially produce the same product, a unit of electricity. There is also an established market for electricity and a known market spot price. However, this is more complicated for recycling phosphorus, since the different technological options produce different products, most of which have different market values or no currently established market at all. Therefore, the CfD scheme, which overcomes some of the issues for RO, would complicate phosphorus recycling in the water industry.

To overcome the issues of price stability in the PRO scheme, fixed buy-out and surplus fees were developed for the PROCs. The fixed buy-out fee is designed to put a maximum price on PROCs that are traded between companies. The surplus fee received is also a fixed amount, but lower than the buy-out fee, which puts a minimum price on a certificate. The upper and lower price limits (as shown in Figure 17) are designed to reduce price volatility and uncertainty, which was a major criticism of RO scheme. The buy-out and surplus fees would ideally be set by Ofwat (the industry's financial regulator) over a certain period of time (5 year periods) to increase price stability and reduce investor risk, with periodic reviews to ensure that the actual amount of phosphorus recycling achieved meets the industry targets. In this analysis, it was assumed that the buy-out price was £1.00 per PROC, and the surplus fee was £0.50 per PROC, and this remained constant throughout the analysis period to 2050. Determining the value of the PROC surplus and buy-out fees that would balance the required investments and result in the phosphorus recycling targets being met at least cost was beyond the scope of this thesis.

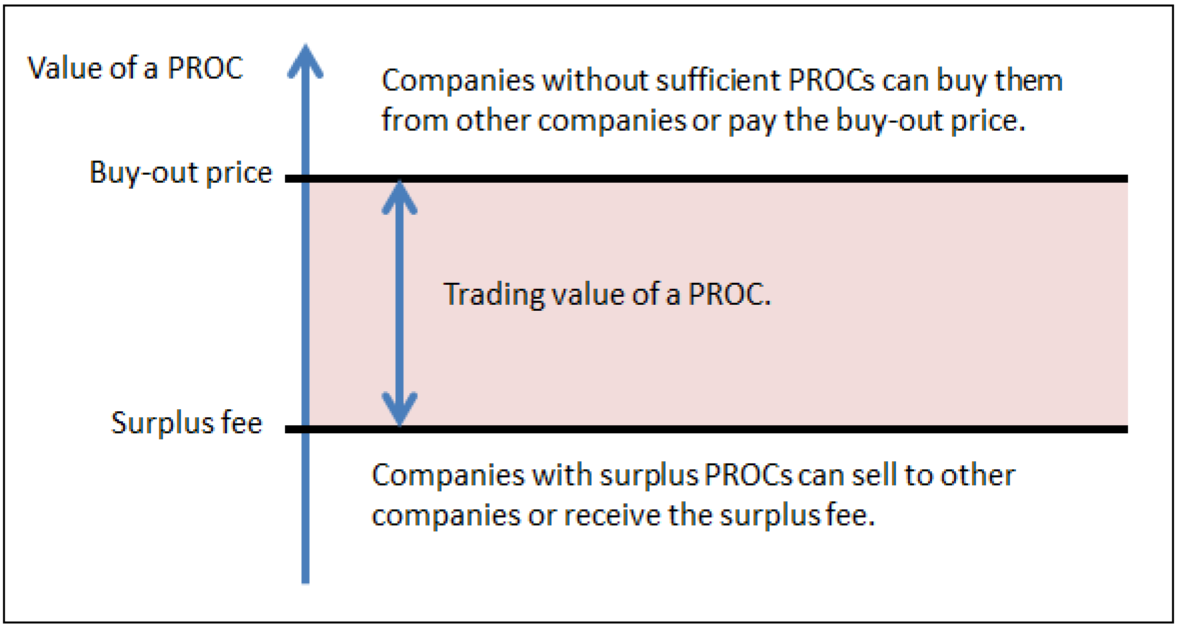


Figure 17: Limiting the trading value of a Phosphorus Recycling Obligation Certificate through the use of the buy-out price and surplus fee.

Under the Renewables Obligation, there was the potential for the ROC price to crash once the industry exceeded its obligation level and therefore required no more ROCs. This could also have been an issue for the PRO scheme, where the traded value of a PROC would crash once all companies had produced or bought enough to meet their obligation. This issue was overcome under the RO by introducing ‘headroom’ in 2009. The headroom approach sets the obligation level above the number of ROCs that are expected to be issued in a given year. Under the PRO scheme, a simpler system was developed where companies with surplus PROCs after trading would receive the surplus fee, which is less than the traded fee but acts like a feed in tariff to provide a minimum, known level of return on investments and encourage companies to exceed their individual phosphorus recycling targets.

A potential issue with this scheme is that in years where there is an overall deficit of PROCs in the industry (i.e. not enough PROCs generated to meet the targets), the value of a PROC would increase to be virtually equal to the buy-out price, and in years of an industry-wide surplus, the traded value could decrease to the value of the surplus fee. The traded value could be further stabilised by setting a pre-determined trading value, such as half way between the buy-out and surplus fee so that both buying and selling parties benefit equally and there is greater financial certainty. In this analysis, it was assumed that all PROCs were traded at £0.75 each.

As with the RO, the funds obtained from buy-out fees will be used to cover the costs of administering the scheme (Ofgem, 2014). Any remaining funds will be used to cover future surplus fee payments or invested to support relevant research projects. The surplus fees will be paid initially from any retained funds from previous years, and then from a proportional, industry-wide charge on the water companies. It was assumed that in a year with an overall deficit, all surplus PROCs were sold to companies with a deficit so no surplus fees were paid, and in a year with an overall surplus all companies with a deficit were able to purchase PROCs from other companies, leaving no buy-out payments to be made.

As mentioned in Section 4.4.1.1, the RO introduced a 'banding' system in April 2009 to encourage investment in a more diverse range of generating technologies by offering additional ROCs per MWh to certain technologies (DECC, 2009). Specifying the water industry obligation as a number of PRO certificates (PROCs) rather than kg phosphorus enables a similar 'banding' system to be introduced. This could be useful to diversify the methods of recycling phosphorus and encourage the development of less established technologies, such as phosphorus recovery from incineration ashes, which may receive more PROCs per kg phosphorus than more established technologies such as sewage sludge recycling. However, as discussed in Section 4.4.1.1, an issue with banding is that it would decouple the number of PROCs allocated and the kg phosphorus recycled, no longer being 1:1. Therefore, controlling the target becomes more difficult. This problem is being addressed in the RO by reducing the value of some technologies to less than 1 ROC/MWh electricity produced, so that the 1:1 ratio is maintained overall. For this analysis, it was assumed that no banding system would be introduced throughout the analysis period to 2050.

There is an issue with how much phosphorus should be considered as recycled for each recycling activity. For sewage sludge, the literature review (Section 4.1.4.1) identified that not all of the phosphorus applied within sewage sludge is available to crops. This is dependent on a number of factors such as the wastewater treatment process, sludge treatment process, soil conditions and crop type. Furthermore, due to nutrient imbalances, sewage sludge applications often result in over applications of phosphorus above crop requirements which could lead to increased runoff to water systems. However, recycling sewage sludge to agricultural land is considered the BPEO, and is becoming increasingly regulated. For example, the Biosolids Nutrient Management Matrix (ADAS, 2013), which came into force in January 2014, limits biosolids applications based on the soil phosphorus status (see Section 4.1.4.1). Imposing a system to calculate the amount of phosphorus that is effectively recycled within sewage sludge would be complicated and costly, and could result in less sewage sludge being recycled, even if permitted under current legislation. Therefore, within this analysis it was assumed that sewage sludge recycling practices that completely complied with the legislation and best practice guidelines, all of the phosphorus was considered as recycled. All other recycling activities, including the use of sewage sludge for forestry, energy crops and land reclamation, and phosphorus recovered from wastewater, sewage sludge and incineration ashes, were also considered as completely recycled, and received 1 PROC for each kg of phosphorus recycled. Sewage sludge sent to landfill, or incinerated without a phosphorus recovery process was not awarded a PROC.

5.4.4 Estimating the response of the water companies

To test how the PRO scheme would be used to increase phosphorus recycling within the UK water industry, three scenarios were developed for the years 2012, 2025 and 2050. The 2012 scenario was established as the current position, while the 2050 scenario incorporates the longer-term goal of achieving 80% phosphorus recycling from wastewater. An intermediate scenario was developed, choosing the year 2025, which is within reasonable planning horizons, but allows for investments to be made in addition to those already planned for AMP6, which runs from 2015-2020. This section sets out the assumptions of how the water companies would respond to meet the targets set under the PRO scheme.

The phosphorus load to UK water companies is likely to increase as a result of the increasing UK population. The population in the UK in 2009 was 62.2 million people (ONS, 2013). It is estimated that in 2012 the UK population was 63.7 million, and will reach 69.2 million by 2025 and 77.0 million by 2050 (ONS, 2013). The size of the water industry (in terms of population equivalent) in 2012 is assumed to be 71.3 million (from the analysis of the water industry, Section 6.1.1), and it is assumed to increase in proportion to population increases. Furthermore, it is assumed that existing WwTWs will increase in size, rather than new WwTWs being built. The increase in size of WwTWs will be proportional to the size of the existing works. The phosphorus load to the industry in 2009 is assumed to be 55 kt P (from the SFA results, Section 6.2.6), and it is assumed that the phosphorus load will also increase in proportion to population increases. The three scenarios presented in this analysis are for 2012, 2025 and 2050. The size of, and phosphorus loads to the industry for these year are presented in Table 14.

Table 14: The estimated size of, and phosphorus loads to the UK water industry in 2012, 2025 and 2050

Year	Size of UK Population (million)	Size of water industry (million p.e.)	P load to the water industry (kt P/year)
2009	62.2	69.6[1]	55.0
2012	63.7	71.3	56.3
2025	69.2	77.4	61.2
2050	77.0	86.1	68.0

Notes: 1) Assume that the size of the water industry has increased in proportion to the size of the UK population.

The amount of phosphorus removal achieved at each WwTWs was assumed based on the level of treatment at the WwTWs. This information was obtained from the water companies. The phosphorus removal assumptions are detailed in Table 15. In practice, phosphorus flows within the influent and effluent should be measured. If measurements were taken only at works >10,000 p.e., of which there are 824 (see Table 21), this would cover over 90% of the total population served in the UK. This would provide a good estimate of phosphorus flows through the company's larger works, and similar assumptions could be used to estimate flows through the smaller works to avoid excessive testing requirements.

Table 15: Phosphorus removal based on level of treatment at wastewater treatment works

Level of treatment	Amount of phosphorus removed from influent (%)
Preliminary	20
Primary	40
Secondary	50
Tertiary (Specific phosphorus removal process)	80
Ultra	95

The ability to trade PROCs is included to encourage the most cost effective investments. When trading PROCs In a year with an overall deficit, it was assumed that PROCs are purchased in proportion to the need of each company so companies with a greater requirement were able to purchase more PROCs, whilst ensuring that the total number of PROCs being bought does not exceed the total amount generated by other water companies. The same principle was applied for trading PROCs in a year with an overall surplus to ensure that companies do not sell more PROCs than they have generated, and that the total amount of PROCs sold does not exceed the amount required. A simplified example is shown in Table 16, where the surplus PROCs generated by Company A are distributed amongst Company B and Company C in proportion to the size of their demand.

Table 16: A simplified example of trading Phosphorus Recycling Obligation Certificates.

Water Company	Surplus PROCs	Number of PROCs sold
A	100	100
B	-100	-25
C	-300	-75

The performance of the water industry in 2012 was based on the information obtained from the water companies regarding the existing infrastructure (Section 6.1) and the assumptions set out previously within this section. The sludge disposal routes were assumed to be the same as in 2009, based on information gathered for the substance flow analysis (Section 6.2), and these are presented in Table 17.

Table 17: Assumed sludge disposal routes in 2012

Water company	Sludge Disposal Routes in 2012 (%)					
	Recycled to agriculture	Composted	Land reclamation	Other (inc. Industrial crops, forestry etc.)	Incinerated	Land fill
Anglian Water	94.9	0.0	4.9	0.2	0.0	0.0
Northern Ireland	0.0	0.0	0.0	0.0	100.0	0.0
Northumbrian Water	89.6	0.0	2.3	8.1	0.0	0.0
Scottish Water	50.0	0.0	0.0	0.0	50.0	0.0
Severn Trent	99.9	0.0	0.0	0.1	0.0	0.0
South West	78.6	0.0	0.0	21.4	0.0	0.0
Southern Water	99.4	0.0	0.0	0.6	0.0	0.0
Thames Water	55.0	0.0	4.9	1.6	38.5	0.0
United Utilities	91.9	2.1	0.0	0.0	6.1	0.0
Welsh Water	93.7	3.9	0.0	2.4	0.0	0.0
Wessex Water	92.9	4.7	2.4	0.0	0.0	0.0
Yorkshire Water	36.6	1.0	11.2	9.7	41.5	0.0

Achieving the phosphorus recycling target for 2025 will require some investments to be made to increase the amount of phosphorus removed from wastewater, recovered through phosphorus recovery technologies, and recycled within sewage sludge. It is assumed that these investments would be made both to achieve river quality objectives and to meet the targets of the PRO scheme at least cost. A number of assumptions have been made about the position of the industry by 2025:

- All WwTWs have a minimum of primary treatment (40% phosphorus removal).
- All WwTWs >10,000 p.e. have a minimum of secondary treatment (50% phosphorus removal).
- All WwTWs >100,000 p.e. have a minimum of tertiary treatment (80% phosphorus removal).
- All WwTWs that had phosphorus consents in 2012 have ultra-treatment (95% phosphorus removal).
- All WwTWs with phosphorus consents in 2012, >100,000 p.e. and with activated sludge secondary treatment have converted to biological phosphorus removal, and have installed phosphorus recovery processes recovering 40% of the phosphorus from wastewater.
- All sewage sludge that was previously disposed of to landfill in 2012 is now used for land reclamation in 2025.
- The remaining sewage sludge disposal routes remaining the same in 2025 as in 2012.
- Assume that no phosphorus recovery processes have been installed for incineration ash.

Similarly, achieving the phosphorus recycling target for 2050 will require increased investments in phosphorus removal and phosphorus recovery technologies. The following assumptions were made about the position of the industry in 2050:

- All WwTWs have a minimum of secondary level treatment.
- All WwTWs >10,000 p.e. have a minimum of tertiary treatment.

- All WwTWs that had phosphorus consents in 2012 now have ultra phosphorus removal (95% phosphorus removal).
- All WwTWs >100,000 p.e. have ultra phosphorus removal.
- All WwTWs >100,000 p.e. have phosphorus recovery processes installed, recovering 40% of the phosphorus removed from wastewater.

It is assumed that the sludge disposal routes for 2050 have changed from 2025. In particular, it is assumed that sewage sludge recycling to land is even more restricted to protect human and environmental health. The following assumptions were made:

- All water companies that incinerated sewage sludge in 2012 now incinerate 75% of their sewage sludge to reduce sludge to agricultural land operations, except for Northern Ireland which still incinerates all of its sludge.
- All companies that previously had no incineration capacity, have increased this to 25% of total sludge disposal to reduce sludge to land applications.
- All companies that previously used sludge for land reclamation now recycle 5% of their sludge for this purpose. This is generally the poorer quality sludges generated.
- The demand for water companies to generate renewable energy through anaerobic digestion means more sewage sludge is diverted from agriculture for other uses, and in particular the growing of energy crops. All companies have increased this to a minimum of 10%, replacing sludge to agricultural land, except for Northern Ireland, which incinerates all of its sewage sludge.

- It is assumed that 60% of the phosphorus in incineration ashes is recovered through a phosphorus recovery process. As a comparison, the sludge strategy in Zurich aims to recover 80% of the phosphorus from mono-incineration ashes (See section 4.4.2).

The assumed sludge disposal routes for the year 2050 based on the existing situation and these assumptions are presented in Table 18.

Table 18: Assumed sludge disposal routes in 2050

Water company	Sludge Disposal Routes in 2050 (%)					
	Recycled to agriculture	Composted	Land reclamation	Other (inc. Industrial crops, forestry etc.)	Incinerated	Land fill
Anglian Water	60.0	0.0	5.0	10.0	25.00	0
Northern Ireland	0.0	0.0	0.0	0.0	100.00	0
Northumbrian Water	60.0	0.0	5.0	10.0	25.00	0
Scottish Water	15.0	0.0	0.0	10.0	75.00	0
Severn Trent	65.0	0.0	0.0	10.0	25.0	0
South West	55.0	0.0	0.0	20.0	25.00	0
Southern Water	65.0	0.0	0.0	10.0	25.00	0
Thames Water	10.0	0.0	5.0	10.0	75.00	0
United Utilities	10.0	5.0	0.0	10.0	75.00	0
Welsh Water	60.0	5.0	0.0	10.0	25.00	0
Wessex Water	55.0	5.0	5.0	10.0	25.00	0
Yorkshire Water	5.0	0.0	10.0	10.0	75.00	0

6 RESULTS AND ANALYSIS

The section presents the results from the analyses that were undertaken to address the knowledge gaps identified in the literature review and to determine if the UK water industry will be required to recycle increased amounts of phosphorus in the future to contribute towards UK phosphorus security. This section presents the results from these analyses, which include:

- The analysis of the current position of the water industry
- The substance flow analysis of phosphorus in the UK
- The analysis of reserve-to-production ratios intensifying global phosphorus scarcity
- The analysis of phosphorus management strategy

6.1 The analysis of the current position of UK water industry

The literature review revealed that there was very little information available about the existing infrastructure in the UK water industry. As established in the methodology (Section 5.1), a large amount of information was gathered from all 12 UK water companies, generating a database containing the name, size, treatment level and method of phosphorus removal for all UK WwTWs. This information was then analysed to determine the potential for the water industry, and the individual water companies, to recover and recycle phosphorus and contribute towards UK phosphorus security. This section presents the results of this analysis, and focusses in particular on:

- The total number and size of UK WwTWs.
- The number and methods of phosphorus removal employed at the WwTWs.
- The relative size and treatment methods employed within the individual water companies
- The potential for struvite recovery at UK WwTWs.

6.1.1 The number and size of UK wastewater treatment works

The UK water companies operate 9,278 WwTWs, which treat the wastewater of the UK population and various industries. Ofwat uses a banding system to classify works in terms of the load they receive, expressed in kilograms of biochemical oxygen demand per day (kg BOD5/day) (Ofwat, 2008). Large works are classified as Band 6 works, having an average daily load >1,500 kg BOD5/day, while small works, of which there are 5 bands, have loads <=1,500 kg BOD5/day (Ofwat, 2008). These loads are converted into population equivalents by assuming that the resident connected population contributes 60 g BOD5/head/day (Ofwat, 2008). The BOD loads and p.e. for different band classifications are shown in Table 19. The number and population of UK WwTWs that fit into each band are shown in Table 20.

Table 19: Band classifications for wastewater treatment works.
Data source: Ofwat, 2008.

Band Classification	BOD load (kg BOD_5/day)	Population equivalent (p.e.)
Small works		
- Band 1	<=15	0 – 250
- Band 2	>15, but <=30	250 – 500
- Band 3	>30, but <=120	500 – 2,000
- Band 4	>120, but <=600	2,000 – 10,000
- Band 5	>600, but <=1,500	10,000 – 25,000
Large works		
- Band 6	>1,500	>25,000

Some of the UK WwTWs are very large, with over 1 million p.e., while many are very small, including septic tanks, serving less than 100 people. There were 75 WwTWs listed with a p.e. of 0, which are classified within the Band 1 group.

Table 20: Number and populations of different bands of wastewater treament works

Band Classification	Number of WwTWs Works	% of all UK WwTWs works	Population served (p.e.)	% of total UK p.e.
Band 6	447	4.8%	58,232,595	81.7%
Band 5	377	4.1%	6,003,218	8.4%
Band 4	1,052	11.3%	4,877,491	6.8%
Band 3	1,443	15.6%	1,498,483	2.1%
Band 2	910	9.8%	325,600	0.5%
Band 1	5,049	54.4%	327,448	0.5%
Total	**9,278**	**100.0%**	**71,264,836**	**100.0%**

The data presented in Table 20 shows that only 447 WwTWs (less than 5% of the total number) are classified as Band 6 works (>25,000 p.e.), but that these works serve a population equivalent of over 58 million people, which is over 80% of the total population served by all UK WwTWs. Assuming that the total phosphorus input to all UK WwTWs is 55.0 kt P/yr (see Section 6.1) and that the phosphorus load to individual WwTWs is proportional to the population size, this suggests that Band 6 works receive around 44.9 kt P/yr. This figure is likely to be an underestimate of the phosphorus received at these works since many larger works will often receive and treat sewage sludge from smaller works (known as satellite sites), which contains the phosphorus removed at those works. Also, imported food waste for anaerobic digestion at WwTWs will increase phosphorus loads to these works. However, neither of these two additional phosphorus loads has been quantified within this study.

The population profile shown in Figure 18 was produced by ranking the WwTWs in order of size (from largest to smallest) and cumulating the p.e. values in order to demonstrate that most of the population are served by a small number of works. These large works are most likely to be targeted for phosphorus recovery technologies.

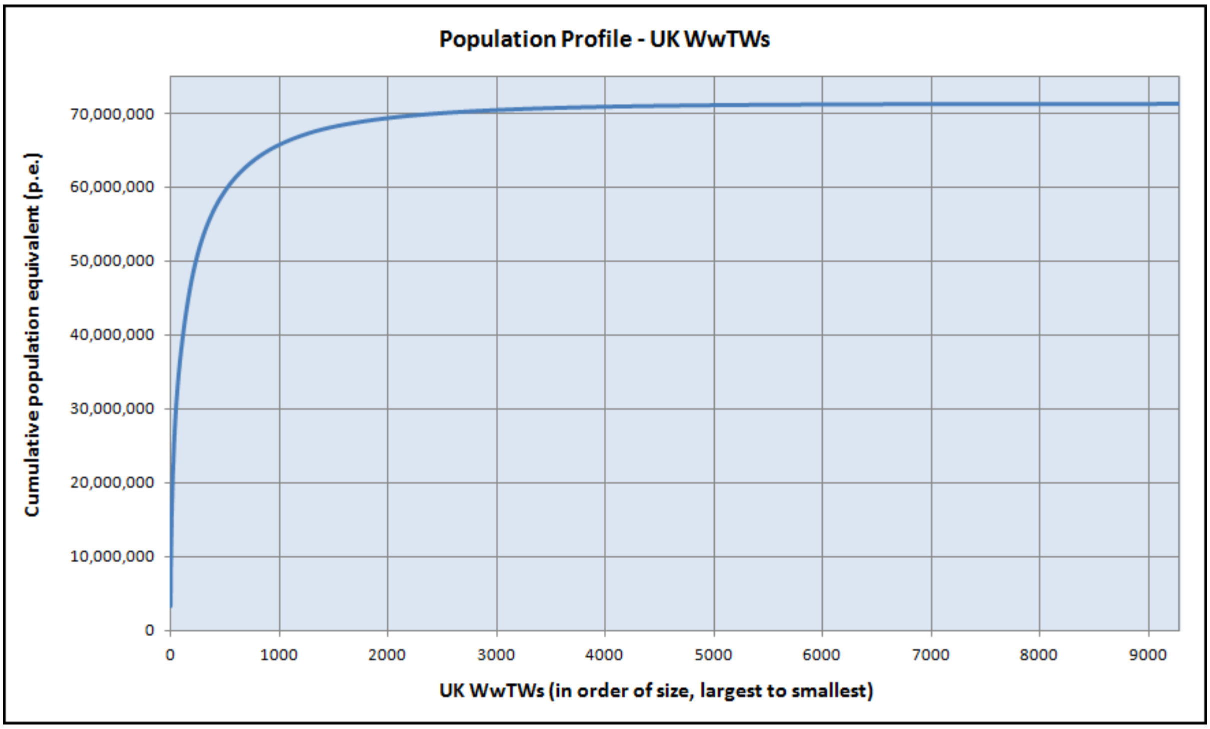


Figure 18: Population profile of UK wastewater treatment works.

The data used to produce Figure 18 revealed that the largest 10 WwTWs in the UK serve 19.7% of the total UK population, while the largest 100 serve 53.5%, and the largest 1000 serve 92.2% of the total population. Table 21 details the populations served by the different sizes of WwTWs.

Table 21: The size and population of the largest wastewater treatment works

Size of works (p.e.)	Number of works	Combined size (p.e.)	% of total population (%)
>1,000,000	5	9,683,742	13.6
>200,000	59	31,725,316	44.5
>100,000	142	42,869,361	60.2
>25,000 (Band 6)	447	58,232,595	81.7
>10,000	824	64,235,813	90.1

6.1.2 Wastewater treatment works with phosphorus removal

In order to recover phosphorus, it must first be removed from the wastewater, and this removal rate is increased when specific phosphorus removal processes are installed (see Section 4.1.3). As shown in Table 22, there are a total of 476 WwTWs in the UK that have phosphorus consents, meaning that the final effluent must be below a specified phosphorus concentration and phosphorus removal processes are usually required to achieve this. These WwTWs serve a population of 20.9 million people. The number of works with phosphorus removal is consistent with the UKWIR estimate for 2010 (478 WwTWs), although the population served is considerably higher than the UKWIR estimate of 16.5 million (UKWIR, 2010).

Table 22: Number and populations of wastewater treatment works with phosphorus removal

Band Classification	Number of works with phosphorus removal	Proportion of all works with phosphorus removal (%)	Population served by works with phosphorus removal (p.e.)	Proportion of total population of works with phosphorus removal (%)
Band 6	164	34.5%	17,749,777	84.8%
Band 5	157	33.0%	2,537,304	12.1%
Band 4	100	21.0%	579,876	2.8%
Band 3	42	8.8%	52,060	0.2%
Band 2	8	1.7%	2,955	0.0%
Band 1	5	1.1%	500	0.0%
Total	**476**	**100.0%**	**20,922,474**	**100.0%**

6.1.3 Methods of phosphorus removal

Table 23 lists the number and size of the WwTWs operating different forms of phosphorus removal. The chemicals used for phosphorus removal have been grouped as either iron compounds, such as ferric or ferrous sulphates and chlorides, or aluminium compounds. Some of the data suggested that either iron or aluminium was employed, or that both were available for use. There were several cases where works operating EBPR process had 'back-up' chemical dosing to overcome variability problems and ensure low effluent phosphorus levels were met. Many of these works mentioned using iron, while none mentioned using aluminium as a back-up chemical, and therefore for the few works where neither chemical was specified, it was assumed that iron was used. Two small works (<2,000 p.e.) were listed as having phosphorus consents, but no phosphorus removal process was required.

Table 23: The methods of phosphorus removal at UK wastewater treatment works

Method of P removal	Number of WwTWs with P removal	Population of WwTWs with P removal (p.e.)	Number of Band 6 WwTWs with P removal	Population of Band 6 WwTWs with P removal (p.e.)
Iron	417	15,146,870	135	12,305,012
Aluminium	12	285,113	2	171,900
Iron and/or Aluminium	21	677,592	10	543,080
EBPR	6	984,918	3	951,482
EBPR with back-up iron dosing.	18	3,825,721	14	3,778,303
None	2	2,260	0	0
Total	**476**	**20,922,474**	**164**	**17,749,777**

As shown in Table 23, most of the phosphorus removal occurring at UK WwTWs involves dosing iron, accounting for nearly 88% of the total number of works with phosphorus removal. This total is increased to 94.5% of the works when allowing for all works applying chemicals for phosphorus removal, including iron, aluminium or both. EBPR processes are often employed at the larger works, therefore in terms of population served, 77% use chemical dosing and 23% use EBPR. However, the majority of the works with EBPR processes also had back-up chemical dosing.

Table 23 also shows that most phosphorus removal is occurring at Band 6 works, representing nearly 85% of the total population served by WwTWs with phosphorus removal processes.

6.1.4 Position of the individual water companies

Developing target wastewater treatment works for phosphorus recovery based on size and treatment type will result in some water companies playing a greater role than others in phosphorus recovery due to their existing infrastructure. Table 24 details the existing infrastructure for all 12 UK water and sewerage companies.

Table 24: The number and size of wastewater treatment works owned by the individual water companies.

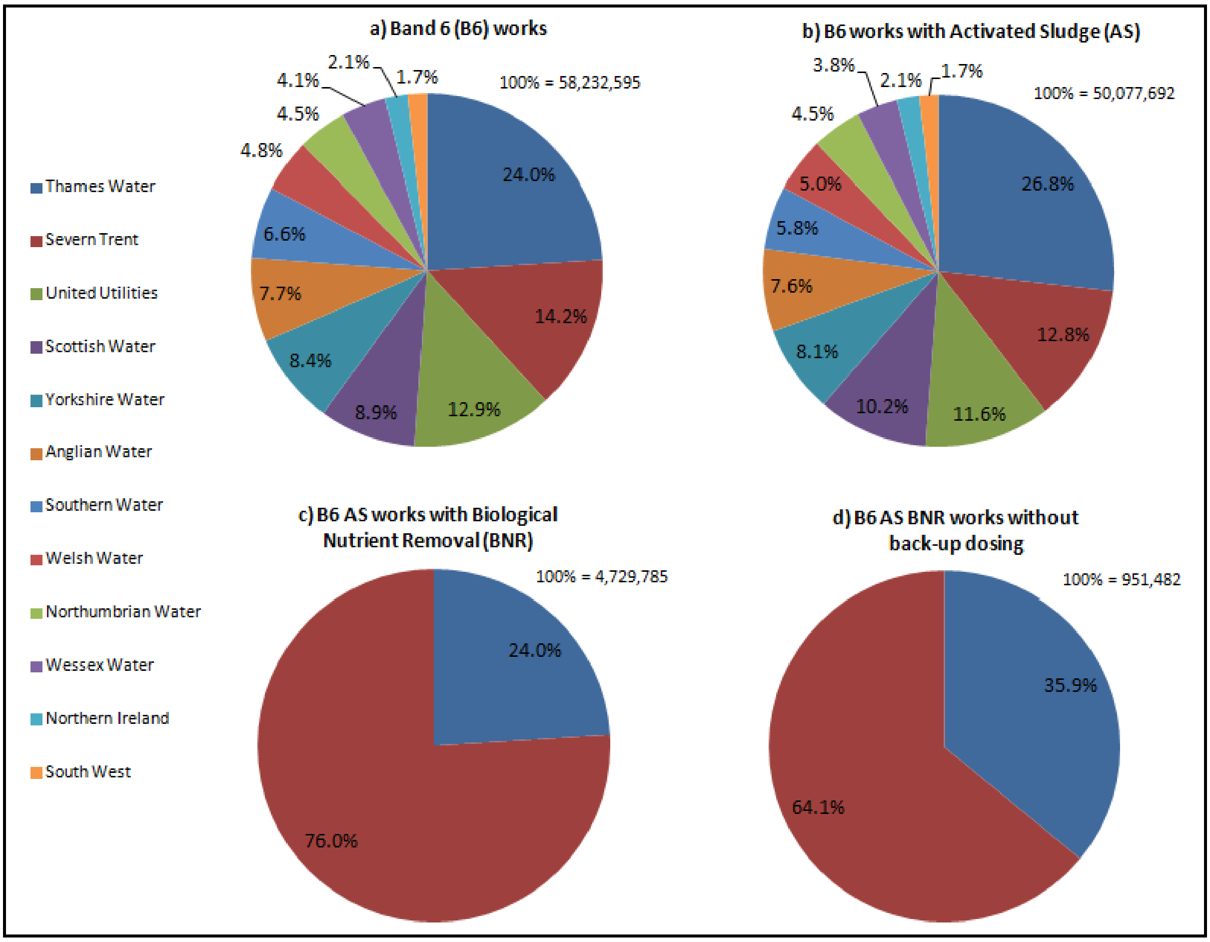
Water Company	No. of works	Total Population (p.e.)	No. of works with P removal	p.e. of works with P removal	No. of Band 6 works	Population of B6 works	Pop. of B6 works with AS	Pop of B6 AS works with EBPR
Anglian Water	1,128	6,759,106	104	3,413,955	50	4,482,537	3,800,097	0
Northern Ireland Water	1,030	1,855,289	14	527,645	14	1,210,624	1,053,116	0
Northumbrian Water	414	3,044,108	12	345,678	22	2,622,317	2,272,106	0
Scottish Water	1,884	6,712,799	22	536,082	37	5,181,218	5,093,695	0
Severn Trent Water	1,024	10,036,893	108	6,894,632	66	8,267,193	6,423,012	3,594,785
South West Water	639	1,713,200	8	80,539	16	1,018,613	865,652	0
Southern Water	371	4,635,739	25	308,887	44	3,822,611	2,898,315	0
Thames Water	350	14,834,460	77	5,762,160	52	13,978,000	13,408,700	1,135,000
United Utilities	572	8,375,511	34	1,767,097	64	7,536,714	5,816,119	0
Welsh Water	838	3,888,293	26	533,386	23	2,817,867	2,502,100	0
Wessex Water	406	3,272,613	39	654,406	25	2,387,087	1,888,616	0
Yorkshire Water	622	6,136,825	7	98,008	34	4,907,814	4,056,164	0
Total	**9,278**	**71,264,836**	**476**	**20,922,474**	**447**	**58,232,595**	**50,077,692**	**4,729,785**

The water industry data presented in Table 24 shows that there is a large difference between water companies in terms of the number and size of WwTWs, and the treatment processes employed. The geographical location of the companies also affects phosphorus removal requirements and the recycling of sewage sludge or other recovered products to agricultural land. Consequently, the potential contribution to UK phosphorus security will differ for each water company.

Table 24 shows that the water companies serve very different sized populations, with Thames Water and Severn Trent Water both serving over 10 million people equivalent, while South West Water and Northern Ireland Water both serve less than 2 million. The companies also have different population profiles. For example, the population served by Thames Water's B6 works amounts to over 94% of their population, while South West Water has less than 60% of their total population served by B6 works. Thames Water's B6 WwTWs serve a population equivalent to nearly 14 million people, or 19.6% of the total UK population equivalent. Assuming that the UK water industry receives 55 kt P/yr within wastewater, then around 10.8 kt P/yr would be received at these works alone. This demonstrates that some water companies will have a bigger stake in UK phosphorus management than others.

The companies also require different amounts of phosphorus removal. For example, Severn Trent Water requires phosphorus removal at 108 works covering 69% of their total population served, while Yorkshire Water requires phosphorus removal at just 7 works covering less than 2% of their total population served. As identified in Section 4.1.5, most phosphorus recovery processes require large works with EBPR. Consequently, as shown in

Figure 19, Thames Water and Severn Trent Water are best positioned to recover phosphorus, since they have more large works with AS and are the only companies operating EBPR systems at these larger works. Thames Water opened the UK's first phosphorus recovery plant at Slough WwTWs in November 2013 (BBC News, 2013), and Severn Trent is expected to start a phosphorus recovery process at Stoke Bardolph WwTWs during 2014.



a) Band 6 (B6) works

b) B6 works with Activated Sludge (AS)

c) B6 AS works with Biological Nutrient Removal (BNR)

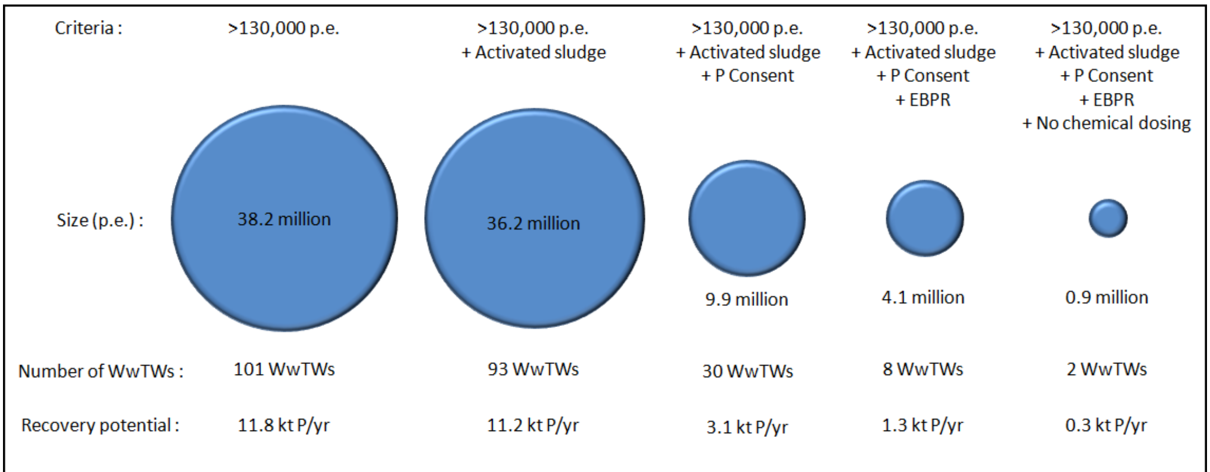
d) B6 AS BNR works without back-up dosing

Figure 19: The size (in population equivalent) of wastewater treatment works owned by different water companies

6.1.5 Potential for struvite recovery at UK wastewater treatment works

As identified in Section 4.1.5, phosphorus recovery as struvite from the liquid phase is seen as the most promising route for phosphorus recovery, although a criticism is that only a small fraction of the phosphorus is recoverable, around 40% of the total inflow to a works with EBPR (Petzet and Cornel, 2011). It has been suggested that if all UK WwTWs >200,000 p.e. were converted to EBPR, the amount of phosphorus recoverable as struvite would be in the region of 1.4 kt P/yr, which is less than 1% of the annual requirement for fertilisers by UK agriculture (UKWIR, 2010). However, according to data collected from the UK water companies (see Table 21), there are approximately 59 works that have a population >200,000 p.e., with a combined population of around 31.7 million, which is almost 45% of the total population served by all UK WwTWs. Assuming this means these works receive 45% of the phosphorus load to UK WwTWs, estimated at 55 kt P/yr, this equates to around 24.5 kt P/yr. If the recovery potential as struvite from the liquid phase is around 40% of the total influent (Petzet and Cornel, 2011), this suggests that 9.8 kt P/year could be recovered as struvite from these large works, which is almost 14% of the 72 kt P/yr estimated to be applied as mineral fertilisers (Section 6.1). Furthermore, according to Britton (2009), the Ostara Pearl process requires a plant size >20 million litres per day, which, assuming that each person uses 150 l/day (Water UK, 2006b), translates into works >130,000 p.e. There are currently 101 WwTWs greater than this size, with a combined population of 38.2 million, or 54% of the total population, suggesting a struvite recovery potential of 11.8 kt P/yr. This represents around 16% of the phosphorus within mineral fertilisers, which would be a considerable contribution to a sustainable phosphorus management system in the UK.

A key obstacle remains that struvite recovery requires large works with AS processes, operating EBPR with minimal chemical addition (Britton, 2009). As shown in Figure 20, applying these constraints dramatically reduces the number and size of works with suitable conditions for struvite recovery. Currently, there are only two works that meet all of Ostara's criteria: Severn Trent Water's Stoke Bardolph WwTWs (581,138 p.e.) and Thames Water's Hogsmill (A&B) WwTWs (342,000 p.e.). These two WwTWs are assumed to have a combined phosphorus load of 0.7 kt P/yr and, assuming only 40% could be recovered as struvite, the potential to recover just 0.3 kt P/yr as struvite. However, Ostara's Pearl Process has recently been installed at Thames Water's Slough WwTWs (238,000 p.e.), which is listed as 'EBPR with back-up chemical dosing', suggesting that additional works within this category may also be suitable for struvite recovery. The results also reveal that installing phosphorus removal processes at the 63 works that are larger than 130,000 p.e., have activated sludge processes but no phosphorus consents would significantly increase the potential for struvite recovery. This investment in phosphorus removal may occur in the future to meet river quality objectives, although EBPR rather than chemical phosphorus removal would be required to recover the phosphorus also. Also, if the phosphorus recovery rate within struvite could be further increased from 40% of the total load to the works, and the required size of the works could be reduced, this would add a significant increase to the overall potential for struvite recovery.



Assumptions: 1) Total UK p.e. = 71.3m. **2**) Total UK P flows = 55 kt P/yr. **3**) P flows are proportional to size of works. **4**) 40% P recoverable as struvite.

Figure 20: The potential amount of struvite recovery from UK wastewater treatment works

6.2 Substance Flow Analysis

Increased use of renewable resources is a key component of increasing resource security. To increase phosphorus security, this involves recycling wastes such as food waste, animal manure and sewage sludge. The literature review revealed that developing a country-scale substance flow analysis is a vital step towards creating a national resource management system. However, despite numerous country-scale analyses being produced for other countries, there was no such analysis for the UK. The principal aim of the SFA for phosphorus in the UK food production system, which was developed as part of this research, was to compare phosphorus flows in the UK water industry to other phosphorus flows within the UK food production system and to determine what contribution increased phosphorus recycling from wastewater could make to resource security in the UK.

This section presents the results of the substance flow analysis and addresses the following questions:

- How reliant is the UK on phosphorus imports?
- What are the main losses in the system?
- How efficient is the UK food production system?
- What are the main flows through the agricultural sub-system?
- What are the main flows through the water industry sub-system?

Also, although a number of country-scale SFAs were developed for other countries, there was no assessment of how the performance of individual countries and their individual sub-systems compared to each other. A number of sustainable indicators were developed for this thesis to enable comparisons between countries and over time, and the key results for other countries are presented in Section 6.2.7. Finally, the limitations of the substance flow analysis are discussed in Section 6.2.8.

6.2.1 Main results

The main results from the SFA are presented in Figure 21, and the methods, assumptions, results and uncertainties are included in Table 25 and Table 26.

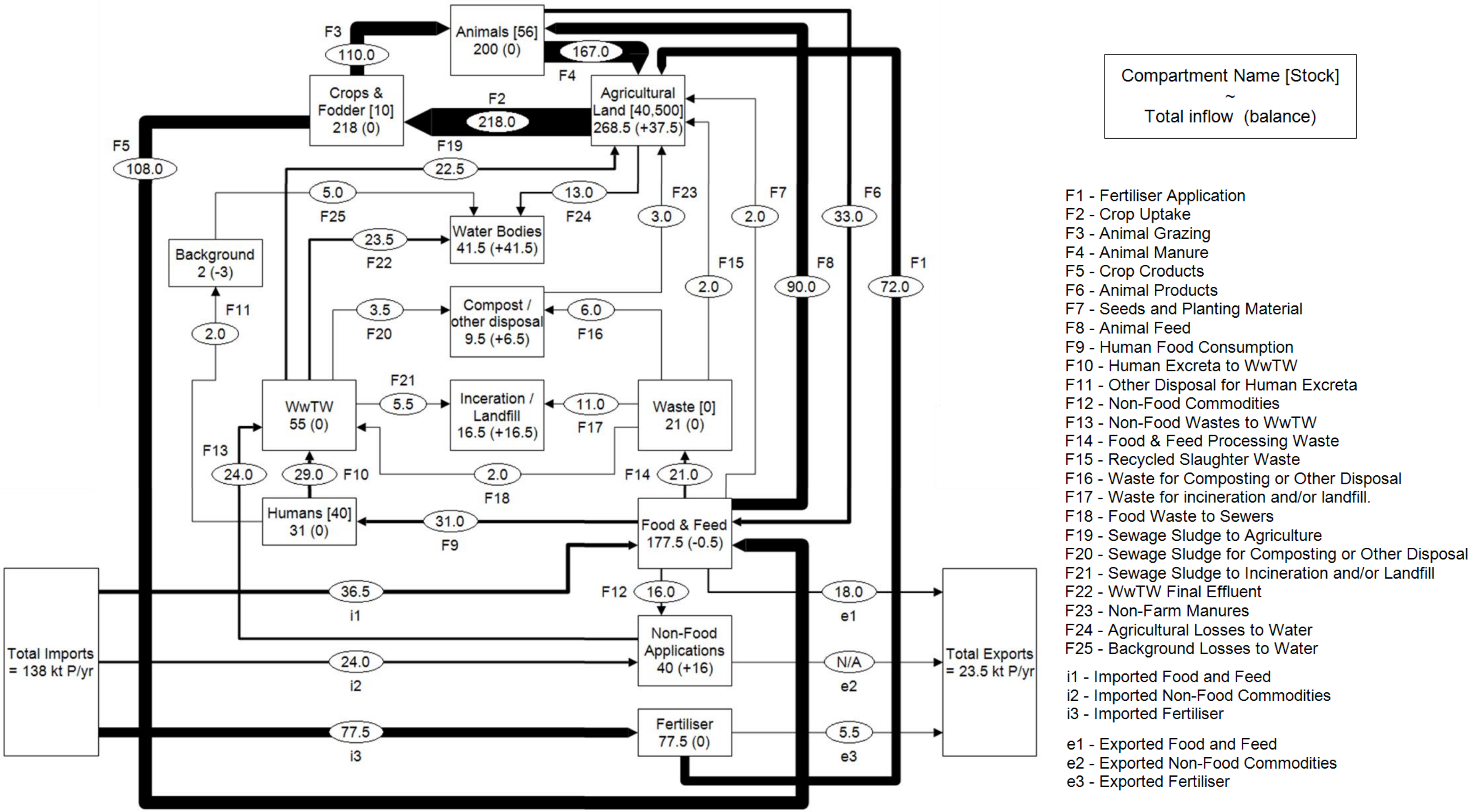


Figure 21: Results of the substance flow analysis for the UK food production and consumption system.

Source: Adapted from Cooper & Carliell-Marquet (2013).

Table 25: The calculations, assumptions, uncertainties and final results for UK phosphorus flows.

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
F1) Fertiliser application	The quantity of P within fertiliser applied to arable and grassland in the UK.	FAOSTAT (2011) estimate of consumption in 2009.	73.8	68.0 [+/- 20.0]	*/ 1.1 [+/- 9.5]	72.0 [+/- 20.0]
		FAOSTAT (2012) estimate of consumption in 2009.	80.3			
		British Survey of Fertiliser Practice (BSFP) 2010 land areas and application rates for 2009 (Defra, 2011b). British application = 70.5 kt P/yr (45.7 kt P/yr to arable land (4.55 million hectares (Mha) @ 10.0 kg P/ha) and 24.8 kt P/yr to grassland (6.3 Mha @ 3.9 kg P/ha)). Northern Ireland total = 2.3 kt P/yr (DARD, 2010b).	72.8			
		BSFP total fertiliser nutrient consumption for UK (Defra, 2011b).	56.3			
		Defra's Soil Nutrient Balance for 2009, inorganic fertilisers (Clothier, 2010).	56.0			
F2) Crop uptake	The quantity of P removed from agricultural land in crops and grasses.	Estimates for UK crop production obtained from Agriculture in the UK 2010 (Defra, 2011a), average nutrient contents taken from the Fertiliser Manual (RB209) (Defra, 2010d), gives UK crop production of 107.3 kt P. Uptake of P from pasture of 110 kt P from Clothier (2010).	217.3	217.0 [+/- 0.3]	*/ 1.2 [+/- 48.0]	218.0 [+/- 48.0]
		Defra's Soil Nutrient Balance for 2009, total phosphorus outputs, including total harvested crops, forage and crop residues (Clothier, 2010).	217.0			
F3) Animal Grazing	The quantity of P taken up during animal grazing.	Defra's Soil Nutrient Balance for 2009 for pasture uptake (Clothier, 2010).	110.0	110.0 [+/- N/A]	*/ 1.2 [+/- 22.0]	110.0 [+/- 22.0]

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
F4) Animal Manure	The quantity of P in animal manure applied to agricultural land, assuming all manure is applied spread to land.	UK animal numbers from the June Census of Agriculture and Horticulture (Defra, 2010f), and applying animal excreta amounts from Withers et al. (2001) of 9.3, 0.99, 2.76 and 0.27 kg P/yr for cattle and calves, sheep and lambs, pigs, and fowl respectively.	178.1	172.0 [+/- 13.0]	*/ 1.4 [+/- 69.0]	167.0 [+/- 69.0]
		UK animal numbers from the June Census of Agriculture and Horticulture (Defra, 2010f). Applying manure outputs during housing period from Defra (2010d). Scaled up for total manure output by assuming equivalent output rates during grazing period. Included sheep and goats, and other livestock outputs of 29 kt P/yr from (Clothier, 2010).	167.2			
		Defra's Soil Nutrient Balance for 2009, livestock manure production (Clothier, 2010).	171.0			
		BSFP 2009 estimates for total applications of organic manure (animal and farmyard manure) to agricultural land (Defra, 2010b). Phosphorus concentrations from Fertiliser Manual (RB209) cited in Defra (2011b). Scaled up to total manure produced by considering housing periods from Defra (2010d). Using animal numbers for NI from DARD (2010a) to scale up to UK scale.	180.6			
		BSFP 2009 estimates for applications of organic manure (animal and farmyard manure) to arable land and grassland (Defra, 2010b). Phosphorus concentrations from Fertiliser Manual (RB209) cited in Defra (2011b). Scaled up to total manure produced by considering housing periods from Defra (2010d). Using animal numbers for NI from DARD (2010a) to scale up to UK scale.	163.4			

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
F5) Crop Products	The quantity of P within crop products	Estimates for UK crop production obtained from Agriculture in the UK 2010 (Defra, 2011a). Average nutrient contents taken from the Fertiliser Manual (RB209) (Defra, 2010d).	107.3	106.0 [+/- 2.0]	*/ 1.2 [+/- 18.0]	108.0 [+/- 18.0]
		Defra's Soil Nutrient Balance for 2009 for total harvested crops and fodder crops (Clothier, 2010).	105.0			
F6) Animal Products	The quantity of P within animal products produced in the UK, including slaughtered animals, milk and eggs.	Slaughtered animals: Estimates for dressed carcase weights of UK animal production from Agriculture in the UK 2010 (Defra, 2011a). Applying P concentrations of 7.2g P/tonne for cattle, 4.6g P/tonne for pigs, 5.6g P/tonne for sheep, and 6.5g P/tonne for poultry (IFP, 2006). UK slaughtered animals contain 20.3 kt P/yr. Milk: 2009 production of 13.2 billion litres (Defra, 2011a) at P content of 0.93 kg P/tonne milk (foodsel, 2008). UK milk production contains 12.0 kt P/year. Eggs: 2009 production of 10.4 billion eggs (Defra, 2011a) at P content of 1.91 mg P/g egg, and assuming each egg weighs 50g. UK egg production containing 1 kt P/yr.	33.3	33.0 [+/- N/A]	*/ 1.2 [+/- 7.0]	33.0 [+/- 7.0]
F7) Seed and Planting Material	The quantity of P within seed and planting material used in UK agriculture.	Estimates for the amount of seed material for wheat, barley and oats from Defra (Defra, 2011a) and potatoes from Defra (Defra, 2010a). Assume P concentrations of crops from The Fertiliser Manual (RB209) (Defra, 2010d).	1.9	2.0 [+/- 0.1]	*/ 1.2 [+/- 0.3]	2.0 [+/- 0.3]
		Defra's Soil Nutrient Balance estimate for seed and planting material input (Clothier, 2010).	2.0			

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
F8) Animal Feed	The quantity of P within animal feed.	Statistics for total compounds, straight concentrates, non-concentrates and inter/intra farm transfer from Agriculture in the UK 2010 (Defra, 2011a). Estimated P contents of 7, 3 and 1 kg P/t for compound concentrates, straight concentrates and low energy feeds respectively from Withers et al. (2001) and assuming that inter/intra farm transfers have similar P content to low energy feeds i.e. 1 kg P/t.	98.2	95.0 [+/- 9.0]	*/ 1.3 [+/- 30.0]	90.0 [+/- 30.0]
		Withers et al. (2001) estimate P in purchased feedstuffs in 1993 of 95 kt P. The total number of cattle, pigs, sheep and poultry decreased by around 7% from 1993 to 2009 (Defra, 2011a). Assume feed requirements reduced proportionally to 88.4 kt P/yr.	88.4			
		Using Defra's Compound Feedstuffs Survey for estimates of the amount and different types of animal feed (Defra, 2012b). Applying P contents of various feedstuffs compiled and supplied by the FAO (2006).	99.4			
		Mass balance estimation, assuming the animal stock remains constant. P within animal feed = P within animal manure (F4 average = 172 kt P) + P within animal products (F6 = 33 kt P) – P intake from grazing (F3 = 110) = 95 kt P.	95.0			

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
F9) Human Food Consumption	The quantity of P within human food, equal to consumption plus waste.	Human consumption: = Average intake of phosphorus in the UK of 1.3 g P/person /day (0.47 kg P/yr) (Expert Group on Vitamins and Minerals, 2003). UK population of 61.8 million in 2009 (ONS, 2010). Suggests consumed food of 29.3 kt P/yr.	29.3	31.0 [+/- 3.0]	*/ 1.3 [+/- 8.0]	31.0 [+/- 8.0]
		Estimates for household and eating out food purchases from Family Food 2009 (Defra, 2010c). P concentrations of various food types from U.S. Department of Agriculture (USDA, 2004). Suggest consumed food of 32.4 kt P/yr.	32.4			
		Human consumption: UKWIR (2010) estimate for the contribution of the human diet to phosphorus loads at UK wastewater treatment works. Wastewater treatment works serve around 96% of the UK population (Defra, 2012f). Assume P consumption is equal to P excretion; therefore food consumption is 31.3 kt P/yr.	31.3			
F10) Human Excreta	The quantity of P within human excreta and food waste discharged to sewers.	Human excreta: Wastewater treatment works serve around 96% of the UK population. Assume human consumption of 31 kt P/yr (See flow F9), with roughly equal amounts in excreta and 96% going to sewers (Defra, 2012f) = 28.8 kt P/yr.	28.8	28.5 [+/- 0.6]	*/ 1.2 [+/- 7.0]	29.0 [+/- 7.0]
		UKWIR (2010) estimated load to WwTWs from urine, faeces and food additives.	28.2			
F11) Excreta – Other Disposal and Leakage	The quantity of P within excreta which is not disposed of to sewers or is lost through leakage.	Assume that there is no increasing stock of human population. Therefore from a mass balance, other disposal or leakage = 31 – 29 = 2 kt P/yr.	2.0	2.0 [+/- N/A]	*/ 1.3 [+/- 0.7]	2.0 [+/- 0.7]

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
F12) Non-Food Commodities	The quantity of P within food type commodities which have uses other than food, feed or seed.	- Crop Products: Domestic uses for crops are estimated by Defra (2011a). P concentrations for various crops are obtained from Defra (2010d). For wheat, barley and oats, which combined account for 68% of P removed in crops, approximately 0.8 kt P is specified as used for "other uses or waste". Assume 50% of this is used for other uses, this amounts to around 0.4 kt P. For oilseed rape, it is estimated that around 5% of domestic consumption is for non-food uses such as biodiesel production (Twining and Clarke, 2009). This is calculated to contain 0.7 kt P. Assume no other significant 'other' or non-food application for crops. Total = 1.1 kt P. - Animal products: It is estimated the UK consumes around 26 kt P/yr within animals, and assuming that around 80% of the body P is found within bones (Withers et al., 2001), around 20.8 kt P/yr is found within the bones of slaughtered animals. The bones have a number of uses, including the production of gelatine, glue, grease and bone meal, although specific data is limited. It is assumed that 10% of the bone P is returned to agriculture (Withers et al., 2001), which contains 2.1 kt P/yr. Of the remaining 18.7 kt P in bone P, it is assumed that 25% is sent for refuse (4.7 kt P/yr), and 75% is used for non-food commodities, containing 14 kt P/yr. Total = (1.1 + 14) = 15.1 kt P/yr.	15.1	16.0 [+/- N/A]	*/ 1.4 [+/- 6.0]	16.0 [+/- 6.0]

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
F13) Non-food waste to sewers	The quantity of P within non-food waste, including P within detergents, P dosing for plumbosolvency and other industrial wastes discharged to sewers.	Detergents: - The amount of phosphorus used in grey water (assumed to be mostly detergents) is estimated at around 0.68g/day/person (Jönsson et al., 2006), for the UK population of 61.8 million (ONS, 2010). = 15.3 kt P/yr - Smith (2007) estimates that 25% of the total phosphorus load to wastewater treatment works is from detergents. Assume that the total load is 48 kt P/yr (UKWIR, 2010). = 12 kt P/yr - UKWIR (2010) estimate of the amount of P within domestic laundry cleaning products (DLCP) and automatic dishwasher detergents (ADW). = 6.8 kt P/yr - Final value = 11 kt P/yr. (2s = 7) P Dosing: - Over 90% of the population receive drinking water dosed with phosphorus to control plumbosolvency at rates of 0.7 to 1.9 mg P/l (UKWIR, 2011a). Approximately 8,500 million litres of drinking water was delivered to households every day in 2009 (Defra, 2011f), and an estimated 2,500 million litres per day was lost through leaked from the system before delivery (Defra, 2011c) Assume 90% of 11,000 Ml/day dosed at 1 mg P/l = 3.6 kt P/yr. - UKWIR estimate of the amount of P dosed to water (UKWIR, 2011b) = 5.0 kt P/yr. - UKWIR (2010) estimate of tap water dosing P load to WwTWs = 4.8 kt P/yr. - Final value = 4.5 kt P/yr. (2s = 1.2)	22.0	22.0 [+/- 10.0]	*/ 1.3 [+/- 7.3]	24.0 [+/- 10.0]

		Industrial Discharges: - Smith (2007) estimates that industry is responsible for around 15% of the total P load to WwTWs. Assume that the load total load is 48 kt P/yr (UKWIR, 2010) = 7.2 kt P/yr. - UKWIR (2010) estimate of the total P load from non-domestic sources (town centres, light industry and traders and runoff) = 5.9 kt P/yr. - Final value = 6.5 kt P/yr. (2s = 1.3)				
F14) Food and Feed Processing Waste	The quantity of P with food and feed processing waste, including wastes from crop and animal products.	- Crop waste: Domestic uses for wheat, barley and oats are estimated by Defra (2011a). P concentrations for various crops are obtained from (Defra, 2010d). Wheat, barley and oats combined account for 68% of P removed in crops, and approximately 0.8 kt P is specified as used for “other uses or waste”. Assume 50% is wasted, which amounts to around 0.4 kt P, and 0.5% of total domestic use for these three crops. Assume 0.5% waste for all other crops used domestically, suggests total crop waste contains 0.57 kt P/yr. - Animal product waste: Total UK domestic consumption of animals is estimated to contain 26 kt P. Assume 80% of body P is found within the bones (Withers et al., 2001), this therefore contains 20.8 kt P. It is assumed that 10% of the bone P is returned to agriculture (Withers et al., 2001), which contains 2.1 kt P/yr. For the remaining 18.7 kt P in bone P, it is assumed that 25% is sent for refuse (4.7 kt P/yr), with 75% (14 kt P/yr) being used for non-food commodities such as gelatine, glue and bone meal. Total bone waste = 4.7 kt P/yr. - Food waste: WRAP (2009) estimate that 20 million tonnes (Mt) of food waste are produced each year (Defra, 2010e) , with households producing 8.3 Mt. Estimates for the quantities of various types of household food waste are provided by WRAP (2009). Applying P concentrations of similar food types obtained from USDA (2004), suggests that 1 Mt of household food waste contains 0.76 kt P. Assuming	20.5	21.0 [+/- 0.7]	*/ 1.3 [+/- 7.0]	21.0 [+/- 7.0]

		that food waste from all sectors has a similar P concentration, this suggests total food waste contains 15.2 kt P/yr. Total = (0.57 + 4.7 + 15.2) = 20.5				
		Estimate for waste by mass balance. Waste = UK crop products (106 kt P/yr) + UK animal products (33.3) + food and feed imports (36) – food and feed exports (18) – Human food consumption (31) – animal feed (90) – Non-food commodities (15.1) = 21.2 kt P/yr.	21.2			
F15) Recycled Slaughter Waste	The quantity of P within slaughter waste which is recycled to agriculture.	Assume that bone P is the only slaughter waste to be returned to agriculture. It is estimated that around 20.8 kt P/yr is found within the bones of slaughtered animals (See F14). It is assumed that 10% of the bone P is returned to agriculture (Withers et al., 2001), which therefore contains around 2.1 kt P/yr.	2.0	2.0 [+/- N/A]	*/ 1.3 [+/- 0.7]	2.0 [+/- 0.7]
F16) Food and Feed Waste for Composting or other disposal.	The quantity of food and feed that is sent for composting, or disposed of to non-agricultural land.	Defra's Municipal Waste Statistics (Defra, 2009c, Defra, 2010g) suggests that for 2008/09 and 2009/10, the average amount of municipal waste sent for recycling/composting was over 10Mt, 38% of the total municipal waste. However, no breakdown for the amount of food waste sent for composting is provided. Assuming that 20 Mt of food waste contains 15.2 kt P/yr (see F14), and that 40% (8 Mt) of waste is sent for composting, this would suggest a P content of 6.1 kt P/yr.	6.1	5.5 [+/- 1.2]	*/ 1.3 [+/- 2.0]	6.0 [+/- 2.0]
		Mass balance approach. Waste to composting = total food waste (21 kt P/yr) – disposal to incineration and landfill (12) – disposal to sewers (2) – direct recycling to agriculture (2.1) = 4.9 kt P/yr	4.9			

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
F17) Waste to Landfill and Incineration	The quantity of P within food and feed waste that is disposed of to landfill and incineration.	<u>Landfill</u> - Crop waste: Assume all crop waste is disposed of to non-agricultural land and therefore none to landfill. - Animal product waste: Animal bone waste sent for refuse is estimated at 4.7 kt P/yr (see F14). - Food waste: Within the Government Review of Waste Policy, it is stated that at least 40% of Britain's food waste is disposed of to landfill (Defra, 2011d) . Taking an average for 2008/09 and 2009/10 of Municipal Waste Statistics (Defra, 2009c, Defra, 2010g), this suggests that 49% of total municipal waste is disposed of to landfill, although this is not specific to food waste. Assume that 20 Mt of food waste contains 15.2 kt P/yr (see F14), and that 50% (10 Mt) of waste is disposed of to landfill, this would contain 7.2 kt P/yr. Total = (0 + 4.7 + 7.2) = 11.9 kt P/yr. <u>Incineration</u> Defra's Municipal Waste Statistics (Defra, 2009c, Defra, 2010g) suggests that for 2008/09 and 2009/10, the average amount of municipal waste sent to incineration with energy recovery was approximately 3.5 Mt. However, it is presumed that incineration with energy recovery would involve mostly paper and card, of which there was around 6.4 Mt produced in 2006 (Defra, 2008) . Therefore, assume no food waste was incinerated.	11.9	11.9 [+/- 0]	*/ 1.3 [+/- 3.7]	11.0 [+/- 4.0]
		- Food waste: From Defra (2009a) it is estimated that 9.3 Mt of biodegradable	11.8			

		municipal waste was disposed of to landfill in 2008-09. Assume that this has a similar P content to household food waste of 0.76 kt P/Mt (see F20), this equates to around 7.1 kt P/yr. - Animal product waste and crop waste as above = 4.7 kt P/yr. - Assume no food waste to incineration, as above.				
F18) Food Waste to Sewers	The quantity of P within human food waste disposed of to sewers.	WRAP (2009) estimate the amount and type of food waste disposed of to sewers. Applying P concentrations from USDA (2004), suggests 1.0 kt P/yr in household food waste disposed of to sewers. WRAP (2009) estimates that 6 million tonnes of food waste is produced from food service, restaurants and others. Assuming that the proportion disposed of to sewers is equivalent to household food waste (22%), and that the food concentration is 0.76 kt P/ Mt food (See F14), this suggests that 1.0 kt P/yr in other food waste to sewers.	2.0	2.0 [+/- 0.0]	*/ 1.3 [+/- 0.6]	2.0 [+/- 0.6]
		UKWIR (2010) estimate of P content of food scraps to WwTWs.	2.0			
F19) Sewage Sludge to Agriculture	The quantity of P in sewage sludge applied to agricultural land.	BSFP estimate of 2.8 Mt biosolids applied to land (Defra, 2010b), assumed to be digested cake containing 7.86 kg P/t (Defra, 2011b)	22.0	30.0 [+/- 20.0]	*/ 1.3 [+/- 8.1]	22.5 [+/- 20.0]
		Defra's Soil Nutrient Balance for 2009, 36 kg P/yr applied as organic fertiliser (Clothier, 2010), of which around 95% is from sewage sludge (Clothier, 2011).	34.2			
		UKWIR (2010) estimate of 24.2 kt P/yr removed in sludge and 68% recycled to agriculture.	16.4			
		Data collected for the June Return 2010 (Environment Agency, 2010) suggests that English and Welsh water companies applied 30.3 kt P/yr to agriculture. Scaled up to UK by assuming equivalent practices in Scotland and NI, and equivalent amounts produced per population number.	34.0			
		ACHS (2009) estimates for sludge spread to agriculture from English and Welsh water companies = 40.0 kt P/yr. Scaled up to UK by assuming equivalent practices in Scotland and NI and equivalent amounts produced per population.	44.9			

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
F20) Sewage sludge for composting or other disposal.	The quantity of P within sewage sludge which is spread to non-agricultural land for land reclamation, industrial crops, composting or composting others.	UKWIR (2010) estimate of 24.2 kt P/yr removed in sludge, with 3% used for land reclamation and 7% for other uses, containing 2.4 kt P/yr.	2.4	3.8 [+/- 4.0]	*/ 1.3 [+/- 1.3]	3.5 [+/- 4.0]
		ACHS (2009) estimates for sludge disposal through composting, cement manufacture, land reclamation and others. Assume similar P concentration as sludge spread to agricultural land, gives 6 kt P/yr through these disposal routes. Scaled up to UK by assuming equivalent practices in Scotland and NI and equivalent amounts produced per population = 6.8 kt P/yr.	6.8			
		Data collected for the June Return 2010 (Environment Agency, 2010) suggests that English and Welsh water companies disposed of 2.0 kt P through means other than to agriculture, incineration or landfill. Scaled up to UK by assuming equivalent practices in Scotland and NI, and equivalent amounts produced per population = 2.3 kt P/yr.	2.3			
F21) Sewage Sludge to Landfill and/or Incineration	The quantity of P within sewage sludge which is either directly disposed of to landfill, or incinerated and then disposed of to landfill.	Direct to landfill: - Sustainability Indicators produced by Water UK (2010) suggest that the percentage of sludge disposed of to landfill was 1.3% in 2008/09 and 0.6% in 2009/10. Assume an average of 1% of total sludge production was disposed of to landfill. For calculating total sludge production, assume average of 78% of sludge was recycled to agriculture for 2008/09 and 2009/10 periods (Water UK, 2010), which contained 30 kt P/ yr (see F15), giving total production sludge production containing 38.5 kt P/yr. 1% to landfill = 0.38 kt P/yr. - Data collected for the June Return 2010 (Environment Agency, 2010) suggests	5.7	5.7 [+/- 1.5]	*/ 1.4 [+/- 2.3]	5.5 [+/- 2.0]

		that English and Welsh water companies disposed of 0.2 kt P landfill. Scaled up to UK by assuming equivalent practices in Scotland and NI, and equivalent amounts produced per population = 0.22 kt P/yr. - UKWIR (2010) estimate of 24.2 kt P/yr removed in sludge, with 2% being disposed of to landfill = 0.48 kt P/yr. - Average value = 0.4 kt P/yr (2s = 0.2) Incineration (assume 100% of ash is disposal to landfill): - Sustainability Indicators produced by Water UK (2010) suggest that the percentage of sludge disposed of through thermal destruction was 13.6 % in 2008/09 and 18.4% in 2009/10. Assume an average of 16% of sludge was incinerated. Assume total sludge contained 38.5 kt P/yr as above. 16% for incineration = 6.2 kt P/yr. - Data collected for the June Return 2010 (Environment Agency, 2010) suggests that English and Welsh water companies incinerated 4.6 kt P. Scaled up to UK by assuming equivalent practices in Scotland and NI, and equivalent amounts produced per population = 5.1 kt P/yr. - UKWIR (2010) estimate of 24.2 kt P/yr removed in sludge, with 19% being incinerated = 4.6 kt P/yr. - Average value = 5.3 kt P/yr. (2s = 1.3) Total = (0.4 + 5.3) = 5.7 kt P/yr.				
F22) WwTWs Final Effluent	The quantity of P within WwTWs effluent discharged to water bodies.	Assuming that all household and industrial discharges to water estimated by White & Hammond (2006) pass through WwTWs, excluding loads from diffuse urban, diffuse industrial and septic tanks.	26.5	25.0 [+/- 2.0]	*/ 1.3 [+/- 8.5]	23.5 [+/- 8.5]
		UKWIR (2010) estimate for P content of WwTWs effluent.	24.2			

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
F23) Non-Farm Manures	The quantity of P within non-farm manures, primarily composted material.	Within the British Survey of Fertiliser Practice 2009 (Defra, 2010b) it is estimated that around 1.4 Mt of non-farm manures were applied to agricultural land. Assuming the P concentration of non-farm manures is equivalent to composted green manure, at 2.62 kt P/Mt (Defra, 2011b), this equates to around 3.7 kt P/yr as non-farm manures. Assume equivalent practices in NI and quantities proportional to population size, suggests P content of non-farm manures of around 3.8 kt P/yr.	3.8	3.0 [+/- 2.0]	*/ 1.3 [+/- 0.8]	3.0 [+/- 2.0]
		Defra's Soil Nutrient Balance for 2009 estimates 36 kt P/yr applied as organic fertiliser (Clothier, 2010), of which around 95% is from sewage sludge, 4% is from urban compost and the remainder from paper and other waste (Clothier, 2011). 4% of total organic fertiliser = 1.4 kt P/yr.	1.4			
F24) Agricultural Losses to Water	The quantity of P lost to water bodies from agricultural land.	White and Hammond (2006) estimated that the total P load to UK waters is approximately 44 kt P/year, of which 12.8 kt P (29%) comes from agriculture. Assume that this remains unchanged for 2009.	12.8	13.0 [+/- 0.1]	*/ 1.3 [+/- 3.5]	13.0 [+/- 3.5]
		UKWIR (2010) estimate phosphorus loads to UK rivers at 32.1 kt P/yr, with 12.9 kt P/yr (40%) from agricultural diffuse pollution.	12.9			

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
F25) Background Losses to Water	The quantity of P lost to water bodies from sources other than agricultural land and WwTWs.	White & Hammond (2006) estimate background losses, including runoff from bogs, marshes, woods and forests, and atmospheric deposition, at 2.8 kt P/yr. Include diffuse urban and industrial, and septic tanks loads of 1.2 , 0.4 and 0.1 kt P/yr respectively.	4.4	4.9 [+/- 1.0]	*/ 1.3 [+/- 1.3]	5.0 [+/- 1.3]
		UKWIR (2010) estimates of phosphorus loads to UK rivers from different sources. The total P load to UK rivers is 32.1 kt P/yr with 5.4 kt P/yr (17%) from background sources, including 1.4 kt P/yr from misconnections and 1.1 kt P/yr from atmospheric deposition.	5.4			
i1) Imported Food and Feed	The quantity of P within imported food (crops, animal products and processed food).	- Crops: Estimates for crop imports obtained from Agriculture in the UK 2010 (Defra, 2011a). Average phosphorus content taken from the Fertiliser Manual (RB209) (Defra, 2010d) = 12.3 kt P/yr - Animal products: Slaughtered animals: Estimates for dressed carcase weights of animal imports from Agriculture in the UK 2010 (Defra, 2011a). Applying P contents of 7.2g P/tonne for cattle, 4.6g P/tonne for pigs, 5.6g P/tonne for sheep, and 6.5g P/tonne for poultry (IFP, 2006). Gives UK animal product imports containing 9.3 kt P/yr. Milk: 2009 imports of 75 million litres (Defra, 2011a) at P content of 0.93 kg P/tonne milk (foodsel, 2008), gives UK milk imports containing 0.07 kt P/year. Eggs: 2009 imports of 2.7 billion eggs (Defra, 2011a) at P content of 1.91 mg P/g egg, and assuming each egg weighs 50g, gives UK egg imports containing 0.3 kt P/yr. Total = 9.7 kt P/yr - Fish: UK fish landings, estimated from the quantities caught in 2009 (MMO,	39.3	36.0 [+/- 6.0]	*/ 1.2 [+/- 7.9]	36.5 [+/- 8.0]

		2011) and the phosphorus concentrations of the different fish types (foodsel, 2008) = 1.1 kt P/yr. - Processed food: Using UK imports and exports of food, feed and drink (Defra, 2011e) for processed food = 7.8 kt P /yr. - Animal feed: Using imported animal feed estimates (which excludes unmilled cereals to avoid double counting) from UK imports and exports of food, feed and drink (Defra, 2011e) and applying P concentrations from foodsel.com (foodsel, 2008) gives 8.4 k t P/yr. Total = (12.3 + 9.7 + 1.1 + 7.8 + 8.4) = 39.3 kt P/yr				
		Using UK imports and exports of food, feed and drink (Defra, 2011e) and applying P concentrations from foodsel.com (foodsel, 2008).	33.3			
i2) Imported Non-Food Commodities	The quantity of P within imported non-food commodities such as detergents, P dosing & industrial applications.	The total P load received at WwTWs by detergents, P dosing and industrial discharges is estimated in Flow 13 at 22 kt P/yr. Since the UK produces no phosphate rock, assume that this was all imported.	22.0	22.0 [+/- N/A]	*/ 1.3 [+/- 7.3]	24.0 [+/- 9.0]
i3) Imported Fertiliser	The quantity of P within imported fertilisers.	FAOSTAT (2011) estimate that UK imports of fertilisers in 2009 contained 71.5 kt P. UK fertiliser production was estimated to contain 7.5 kt P, which must also have been imported. Therefore, total imports of 79 kt P.	79.0	78.0 [+/- N/A]	*/ 1.1 [+/- 7.8]	77.5 [+/- 8.0]

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
e1) Exported Food and Feed	The quantity of P within exported food and drink.	- Crops: Estimates for crop exports obtained from Agriculture in the UK 2010 (Defra, 2011a). Average nutrient contents taken from the Fertiliser Manual (RB209) (Defra, 2010d) = 13.6 kt P/yr Animal products: Slaughtered animals: Estimates for dressed carcase weights of animal exports from Agriculture in the UK 2010 (Defra, 2011a). Applying P contents of 7.2g P/tonne for cattle, 4.6g P/tonne for pigs, 5.6g P/tonne for sheep, and 6.5g P/tonne for poultry (IFP, 2006). Gives UK animal product exports containing 3.6 kt P/yr. Milk: 2009 exports of 433 million litres (Defra, 2011a) at P content of 0.93 kg P/tonne milk (foodsel, 2008), gives UK milk exports containing 0.4 kt P/year. Eggs: 2009 exports of 222 million eggs (Defra, 2011a) at P content of 1.91 mg P/g egg, and assuming each egg weighs 50g, gives UK egg exports containing 0.02 kt P/yr. Total exports = 4.0 kt P/yr - Processed food: Using UK imports and exports of food, feed and drink (Defra, 2011e) for processed food = 2.0 kt P/yr. - Animal feed: Using exported animal feed estimates from UK imports and exports of food, feed and drink (Defra, 2011e) and applying P concentrations from foodsel.com (foodsel, 2008) gives 1.4 kt P/yr. Total = (13.6 + 4.0 + 2.0 + 1.4) = 21.0 kt P.	21.0	18.0 [+/- 6.0]	*/ 1.2 [+/- 4.0]	18.0 [+/- 6.0]
		Using UK imports and exports of food, feed and drink (Defra, 2011e) and applying P concentrations from foodsel.com (foodsel, 2008).	14.9			

Flow Number and Name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[1] [+/- 2s] (kt P/yr)	Average Confidence interval.[2] [range] (kt P/yr)	Final Value[3] [95% confidence limits] (kt P/yr)
e2) Exported Non-Food Commodities	The quantity of P within exported non-food commodities.	Insufficient data available. Assumed to be a very minor flow since the UK produces no phosphate rock.	0	0	0	0
e3) Exported Fertilisers	The quantity of P within exported fertilisers.	FAOSTAT (2011) estimate that UK exports of fertilisers in 2009 contained 5.3 kt P.	5.3	5.3 [+/- N/A]	*/ 1.1 [+/- 0.5]	5.5 [+/- 0.5]

Footnotes:

1) The average value from the various calculations for each flow. This value was entered into the STAN program before the balancing application was performed. The +/- value in the square brackets represents the 95% confidence limits for the average value, calculated using 2 standard deviations.
2) A confidence interval was developed for each calculation following the method described in Section 4.1 and the average confidence interval for each flow (rounded to 1 decimal place) is presented here. This average value was used to produce the range shown in the square brackets, which represents 95% confidence limits. The largest range from this method or the standard deviation method was used in the STAN program.
3) These final results were produced by the STAN program after balancing the flows and validating the model. The 95% confidence limit for each flow is the larger result of the two methods of calculation described above.

Table 26: The existing stock, inputs, outputs and accumulations for the main processes.

Process Name	Existing stock - Calculations, assumptions and references.	Existing Stock (kt P)	Total Input (kt P/yr)	Total Output (kt P/yr)	Accumulation (Kt P/yr)
Agricultural Land	Smil (2000) assumes that the top 50cm of soil contains roughly 3.75 t P/ha, which suggests that grass and arable land contain 23.6 Mt and 16.9 Mt P respectively, giving a total of 40.5 Mt of P within the soil. However, only a fraction of this is available to plants.	40,500.0	268.5	231.0	37.5
Animals	Animal numbers for cattle, pigs, sheep, poultry and others obtained from the June Census of Agriculture and Horticulture (Defra, 2010f). Using phosphorus contents of 4,300, 460, 280 and 13 g P/animal for cattle, pigs, sheep and poultry respectively (IFP, 2006).	56.0	200.0	200.0	0.0
Crops & Fodder	Using estimates from Defra (2012a) for cereal stocks held at ports, co-ops and merchants for March 2009, and on farm stocks of wheat, barley and oats in June 2009 from Defra (2012c). Applying P contents from Defra (2010d), gives 10.4 kt P. Stock will vary over the year.	10.0	218.0	218.0	0.0
Food & Feed	There will be a stock of P held within food and feed at food stores, distributers and within homes and businesses. It is expected that the turnover of food and feed is fast, so the amount held at any given time will be relatively small. This quantity has not been calculated.	Unknown, minor.	177.5	178.0	-0.5[a]
Humans	Office for National Statistics estimates for mid-2009 population of 61.8 million people in the UK (ONS, 2010). Assume the phosphorus content of an adult is around 650g (de Haes et al., 2009, Brunner, 2010). Therefore , the UK population contains around 40.2 kt P.	40.0	31.0	31.0	0.0
Waste	Assume no accumulation within this process. Wastes are moved to other processes, such as landfill or other disposal.	0.0	21.0	21.0	0.0
Non-Food Applications	Stored non-food commodities, such as detergents held by distributers, represent a stock of P, although this is assumed to be relatively small and has not been calculated within this study.	Unknown, minor.	40.0	24.0	16.0

Process Name	Existing stock - Calculations, assumptions and references.	Existing Stock (kt P)	Total Input (kt P/yr)	Total Output (kt P/yr)	Accumulation (Kt P/yr)
WwTWs	Assume no accumulation at WwTWs and therefore no significant stock of P. At any given time, the stock of P could include P within wastewaters, P in sludge undergoing digestion or stored for later treatment or disposal. This is assumed to be a minor amount and has not quantified for this analysis.	Unknown, minor.	55.0	55.0	0.0
Water Bodies	A stock of P will have accumulated in the sediments of rivers, lakes and reservoirs, whilst some will pass into the seas surrounding the UK. This amount has not been quantified but it is assumed that it will be large considering the amounts of P entering the system.	Unknown, large.	41.5	0.0	41.5
Compost/other disposal	This stock of P within compost, or in non-agricultural land used for waste disposal not been quantified, but is assumed to be a relatively small amount.	Unknown, minor.	9.5	3.0	6.5
Incineration / Landfill.	After many years of disposing biodegradable wastes to landfill site, these are expected to contain a significant amount of P. This value has not been calculated.	Unknown, large.	16.5	0.0	16.5
Background	The amount of P in non-agricultural land is unknown, but is expected to be relatively large.	Unknown, large.	2.0	5.0	-3[b]
Fertiliser	The stock of fertilisers stored by distributers or farmers has not been calculated for this analysis. It is assumed to be a minor amount for most of year.	Unknown, minor	77.5	77.5	0.0

Footnotes:

a) Due to rounding errors.

b) The net loss from background sources is the result of additional inputs not being quantified within this analysis. It is expected that this would result in a net accumulation.

6.2.2 Net imports to the UK

Without any phosphate rock reserves, most countries in Europe are net importers of phosphorus. As presented in Figure 22, the UK imports a total of 138.0 kt P/yr, mostly within fertilisers but also as food, animal feed and non-food commodities such as detergents. Total exports amount to 23.5 kt P/yr, resulting in a net import of around 114.5 kt P/yr or around 1.9 kg P/person. This demonstrates that the UK food production system is heavily reliant on imports and potentially vulnerable to rising prices and supply disruptions.

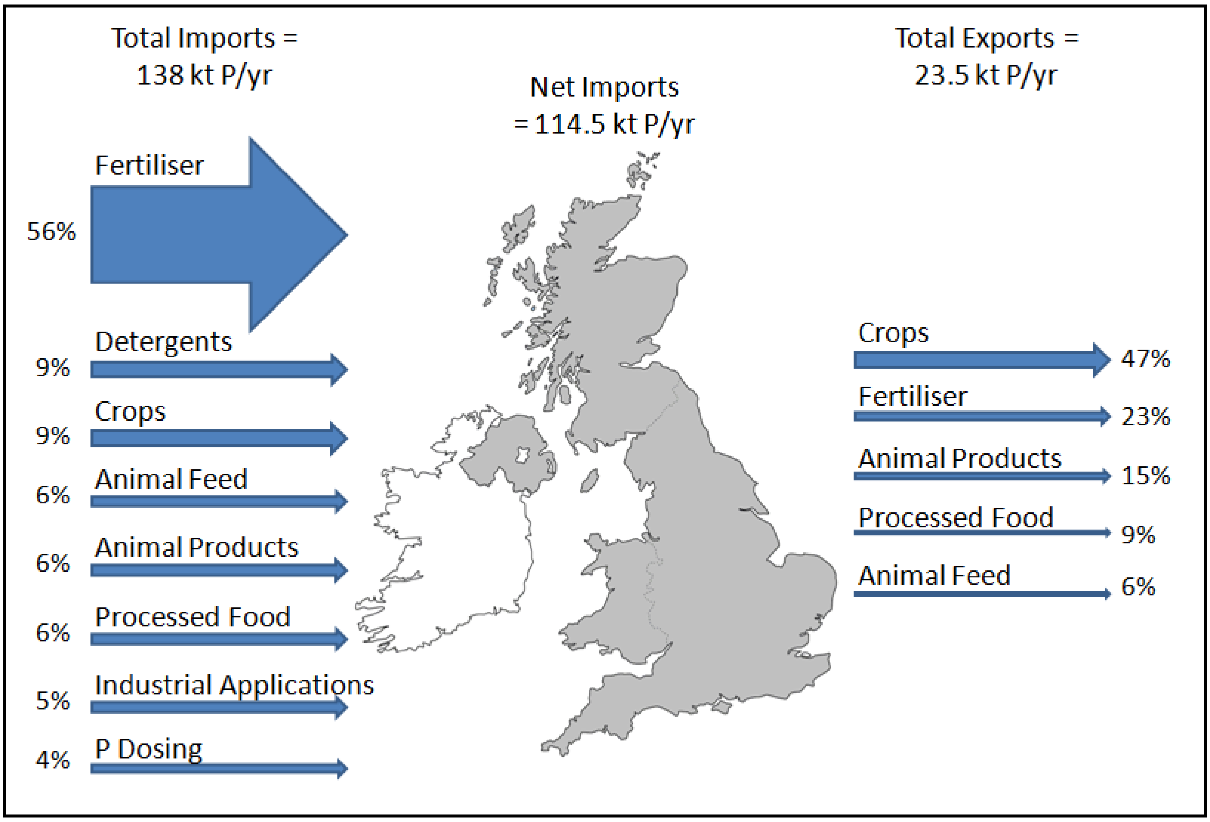


Figure 22: UK phosphorus imports and exports.

Source: Cooper & Carliell-Marquet (2013) (Appendix B).

6.2.3 Accumulations and losses within the UK

The net import of 114.5 kt P/yr represents an annual accumulation of phosphorus within the UK. As shown in Figure 23, the largest proportion of this overall accumulation is due to losses to water bodies, with around 41.5 kt P/yr accumulating in, and polluting UK water systems. Some of the phosphorus will pass into the seas around the UK, although this amount has not been quantified within this analysis. This phosphorus can cause environmental damage through eutrophication and must be tackled in order to meet the Water Framework Directive (WFD) targets (see Section 4.1.2.2). The largest contributor of phosphorus losses to water bodies is from final effluent from WwTWs, estimated to contain 23.5 kt P/yr, which represents around 57% of the total losses to water bodies. Diffuse pollution from agriculture is estimated at 13.0 kt P/yr. Evidence suggests that point sources rather than diffuse sources pose the greater risk for eutrophication in UK rivers (Jarvie et al., 2006), therefore from both a resource scarcity and pollution perspective, it is suggested that the greatest emphasis should be placed on increased phosphorus removal and recovery at WwTWs.

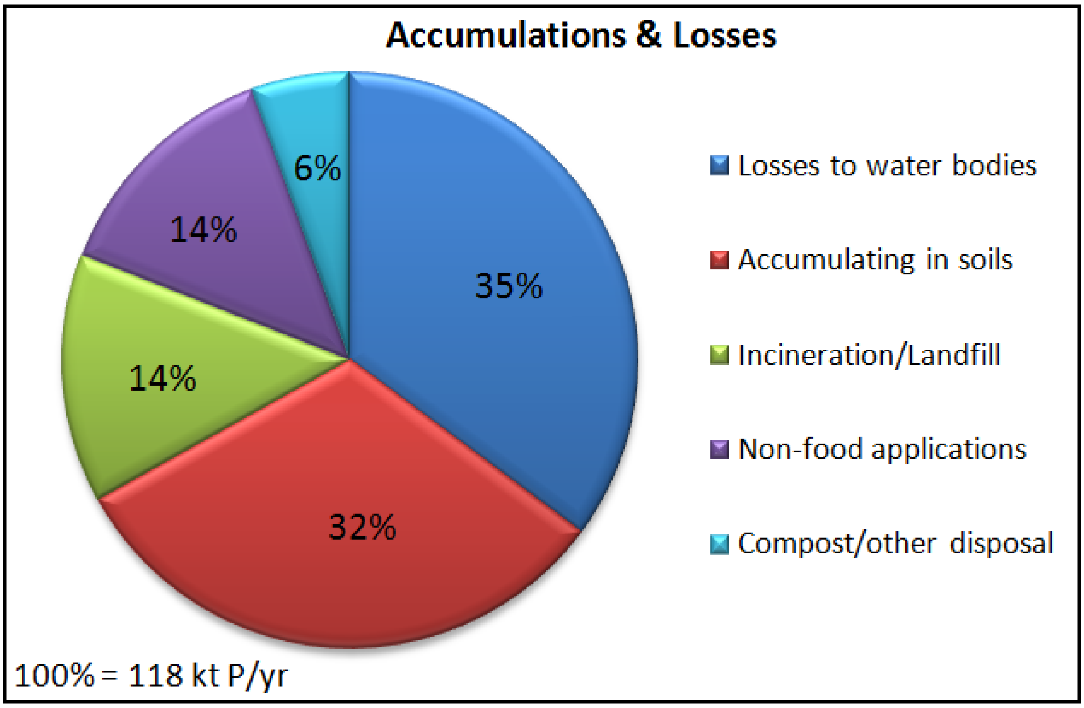


Figure 23: UK accumulations and losses.

A similar amount of phosphorus is accumulating in the soils each year, estimated at around 37.5 kt P/yr, which is equivalent to over 50% of the amount of phosphorus within mineral fertiliser applications. Another major loss within the UK is the loss of phosphorus to landfill, estimated to contain around 16.5 kt P/yr. The largest proportion of this is within food waste, which is contains around 7.0 kt P/yr. This is a considerable amount when compared to the 31.0 kt P/yr consumed by the UK population. Sewage sludge incineration ash containing 5.5 kt P is assumed to be disposed of to landfill and represents a significant loss of phosphorus. Alternative disposal methods for sludge, or phosphorus recovery from the sludge ashes should be explored in order to reduce and recycle these losses.

6.2.4 The efficiency of the UK food production system

The primary goal of the UK food production system is to provide food for the UK population and produce export commodities. These desirable end products are estimated at 29.0 kt P/yr in human food consumption, 18.0 kt P/yr in exported food and feed, and a further 5.5 kt P/yr in exported fertilisers, giving a total of 52.5 kt P/yr. In order to produce these final products, the UK imports around 77.5 kt P/yr within fertilisers and around 36.5 kt P/yr within food and feed, giving a total of 114.0 kt P/yr. The efficiency of the food production system in the UK in converting inputs (114.0 kt P/yr) into desirable end products (52.5 kt P/yr) is around 46%.

6.2.5 The agricultural sub-system

The largest phosphorus flows in the UK are associated with agriculture. The total input to agricultural land, which includes all arable land and grassland, is estimated at 268.5 kt P/yr, and consists of mineral fertiliser (27%), manure (62%), sewage sludge (8%) and others (3%). Inputs to arable land are estimated at 125.5 kt P/yr and inputs to grassland estimated at 143.0 kt P/yr. The outputs of crops and grasses amount to 108.0 and 110.0 kt P/yr respectively, giving a total output of 218.0 kt P/yr. The efficiency of the agricultural system in converting phosphorus inputs (268.5 kt P/yr) into outputs (218.0 kt P/yr) is around 81%, with an annual surplus of 50.5 kt P/yr. Agricultural losses to water are estimated at 13.0 kt P/yr, giving an annual soil accumulation of 37.5 kt P/yr. Over two thirds of the phosphorus accumulation in UK soils is occurring in grasslands, where phosphorus inputs are dominated by animal manure applications (79%), suggesting that the over use of animal manures is responsible for most of the soil accumulation. This accumulation is likely to be increased in areas of intensive animal production due to the challenges of transporting and effectively distributing this bulky material.

Agricultural animals generate large phosphorus flows within the UK. The inputs and outputs were balanced to fit the assumption that the stock remains constant. The inputs to animals were consumption of grasses (110.0 kt P) and animal feed (90.0 kt P), totalling 200.0 kt P/yr, while the main outputs are manure (167.0 kt P) and animal products (33.0 kt P). This suggests that the efficiency of the system in converting inputs into animal products is only 16.5%, with 83.5% of the inputs being converted into manure. However, the analysis is further complicated since most of the phosphorus within these animal products is found within the bones of slaughtered animals, estimated at around 16.0 kt P/yr, which is assumed to be mostly used for industrial purposes or wasted. Also, the manure which is assumed to be a waste product is mostly recycled to agricultural land and has a value as a fertiliser, reducing the requirement for mineral fertiliser applications (Defra, 2010b). However, it is difficult to determine how much of the animal manure is being effectively recycled and how much is being over applied.

The Food & Feed system receives inputs from agriculture as crops and animal products, as well as imported food and feed material. The total inputs to the system are equal to 177.5 kt P/yr and the outputs contain 178.0 kt P/yr. It is assumed that there is no accumulation within this system and the slight difference between inputs and outputs is due to rounding errors. Animal feed represents the largest output, estimated to contain around 90.0 kt P/yr. Humans consume much smaller amounts of phosphorus by comparison, estimated at 31.0 kt

P/yr. It is estimated that this system produces around 21.0 kt P/yr as waste, giving an efficiency of 88%.

6.2.6 The UK water industry sub-system

The UK water industry receives considerable amounts of phosphorus within wastewaters at WwTWs, estimated in this analysis at 55.0 kt P in 2009. This is either discharged to water bodies or removed within sewage sludge. As shown in Figure 24, it is estimated that around 23.5 kt P/yr is discharged in the final effluent, suggesting a removal efficiency of around 57%. Of the 31.5 kt P removed within sewage sludge, approximately 71% is recycled to agriculture, 17% is either sent directly to landfill or more often incinerated with the ashes assumed to be sent to landfill, and 11% is used for composting, spreading on non-agricultural land or used to grow energy crops. The amount of phosphorus recycled to agriculture within sewage sludge, around 22.5 kt P/yr, is approximately 41% of the influent phosphorus, and represents around 8% of the total phosphorus input to agricultural land. However, in 2009 the area of land utilised for sludge applications in Great Britain was around 164,000 ha (Environment Agency, 2010), which represents just 1.5% of the total agricultural area (Defra, 2010b). This suggests that sewage sludge applications are currently applying phosphorus at rates of around 137.0 kg P/ha/year, which is significantly above crop requirements. The Biosolids Nutrient Management Matrix (see Section 4.1.4.1), which came into force in January 2014, now limits biosolid applications based on the soil phosphorus status and will act to reduce over applications to soils that have high P-index levels (ADAS, 2013).

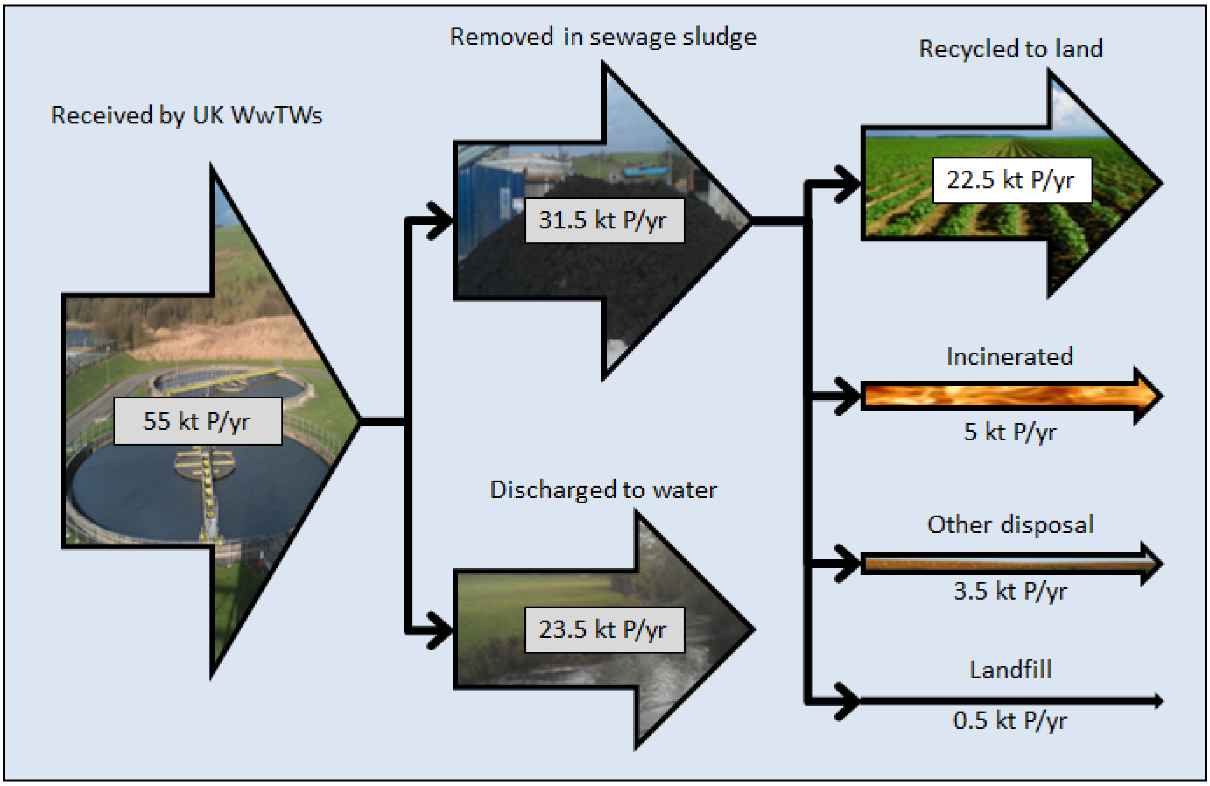


Figure 24: Phosphorus flows through UK wastewater treatment works.

Source: Adapted from Cooper & Carliell-Marquet (2013).

6.2.7 Sustainable indicators

Most of the results from this analysis have been presented using total quantities of phosphorus (in kt P), as opposed to using kg P/ha in agriculture or kg P/capita throughout the whole system. This method is useful for identifying the major flows and losses, and monitoring changes over time within a single country, but is less suited for comparisons with other countries that have different population sizes and agricultural areas. For useful comparisons between countries, the results of a phosphorus SFA need to be presented in kg P/ha, kg P/cap, or through efficiency estimates.

A number of indicators of sustainable phosphorus practices were developed for this research. The development of these indicators is necessary to monitor changes over time, to set targets to work towards, and to compare one country's performance to another. These indicators are described below and a comparison of results obtained from other national-scale SFA studies is presented in Table 27.

- **Net imports** (kg P/person) – The net import figure reveals how reliant a country is on imported phosphorus, such as fertilisers, food and feed. Net imports indicate accumulations within agricultural soils and losses to water bodies and landfill sites. Countries producing and exporting phosphate rock may show negative values, i.e. net exports.
- **Agricultural efficiency** (%) – Calculated by dividing phosphorus outputs by phosphorus inputs. Values below 100% mean that phosphorus is either accumulating in the soil, or is being lost through erosion or runoff. This calculation does not consider crop uptake of soil phosphorus reserves, therefore outputs could exceed inputs leading to efficiency estimates above 100%.
- **Agricultural input from mineral fertilisers** (%) – a measure of how reliant the agricultural system is on mineral fertilisers. This value would be reduced in a progressively closed-loop system with effective recycling of wastes. This measure does not consider imported food or feed, which may be providing some of the phosphorus in the recycled wastes, or the use efficiency of inputs.
- **P recycled from wastewater** (%) – A measure of how much of the phosphorus received at WwTWs is being recycled to agriculture as sewage sludge or other recovered products, or used in industrial processes. This measure encompasses both phosphorus

removal rates at WwTWs and recycling rates of that removed phosphorus. The effectiveness of recycling operations may need to be considered.

- **Losses to water bodies and landfill** (kg P/person) – This measure includes two of the major sinks of phosphorus presented on a per person basis. A reduction would entail reducing losses to water, which cause pollution, reducing waste throughout the whole system and increasing recycling rates. This indicator would not be as effective for addressing water pollution compared to measures of water quality.

Table 27: A comparison of results from other substance flow analyses

Source: Cooper and Carliell-Marquet (2013) (Appendix B).

SFA study	Scale	Year	Net imports (kg P/cap.)	Agricultural efficiency (%)	Agricultural input from mineral fertilisers (%)	P recycled from wastewater (%)	Losses to water bodies and landfill (kg P/cap.)
Cooper & Carliell-Marquet (2013)	UK	2009	1.9	81%	27%	41%	0.9
Senthilkumar et al. (2012)	France	2002-2006	4.7	72%	37%	28%	2.2
Smit et al. (2010)	Netherl-ands	2005	3.8	61%	24%	6%	1.8
Antikainen et al. (2005)	Finland	1995-1999	-	51%	61%	24%	1.1
Seyhan (2009)	Austria	2001	4.0	-	43%	18%	-
Seyhan (2009)	Turkey	2001	4.0	77%	82%	0%	2.3
Suh and Yee (2011)	US	2007	-4.6	76%	81%	-	-
Cordell and White (2010)	Australia	2006/07	-	12%	47%	33%	0.4
Matsubae-Yokoyama et al. (2009)	Japan	2002	5.9	25%	73%	47%	1.2
Chen et al. (2008)	China	2004	-	46%	52%	-	-
Ott and Rechberger (2012)	EU15	2006-2008	4.7	65%	37%	37%	2.0

Based on the indicators presented in Table 27, the UK is performing well compared to most other countries for which data was obtained, including the EU15. In particular, the UK has the lowest net imports per person and the highest agricultural efficiency of all countries considered. However, as shown in Figure 25, the year 2009 was a year of relatively low fertiliser application which would have had a positive impact on many of these indicators if crops yields were maintained by accessing existing soil reserves.

6.2.8 Limitations

There are a few aspects of the SFA which could limit the application of the data for planning and phosphorus management. This SFA was based on the year 2009, chosen as the most recent year at the time of writing for which most of the data was freely available, but this data is already a few years out of date. For some flows, such as fertiliser application, this is important as annual variations can be large. As shown in Figure 25, fertiliser applications rates have been steadily decreasing for many years, with application rates to arable and grass land being around 60% lower in 2009 than in 1985. In fact, the year 2009 represented the lowest fertiliser application since the survey began, being around 25% lower than in 2008 (Defra, 2010b). This was due to a combination of reduced average application rates and a reduction in the proportion of land receiving an application (Defra, 2010b). Phosphate applications in 2010 were considerably higher as farmers were compensating for previous under applications (Defra, 2011a).

For other flows, annual variations are less significant. For example, the total phosphorus removed as crops in 2009 is estimated at around 108.0 kt P, which is slightly less than the

116.0 kt P estimated to have been removed during 2008 (7% reduction), despite the large decreases (25% reduction) in mineral fertiliser applications. Since yields did not reduce by a proportional amount, this suggests that during 2009 a greater amount of phosphorus was withdrawn from the existing stock within the soil. Also, the phosphorus flows associated with human consumption, excreta and wastewater treatment are less sensitive to variations, but would be expected to increase in line with population growth in the UK.

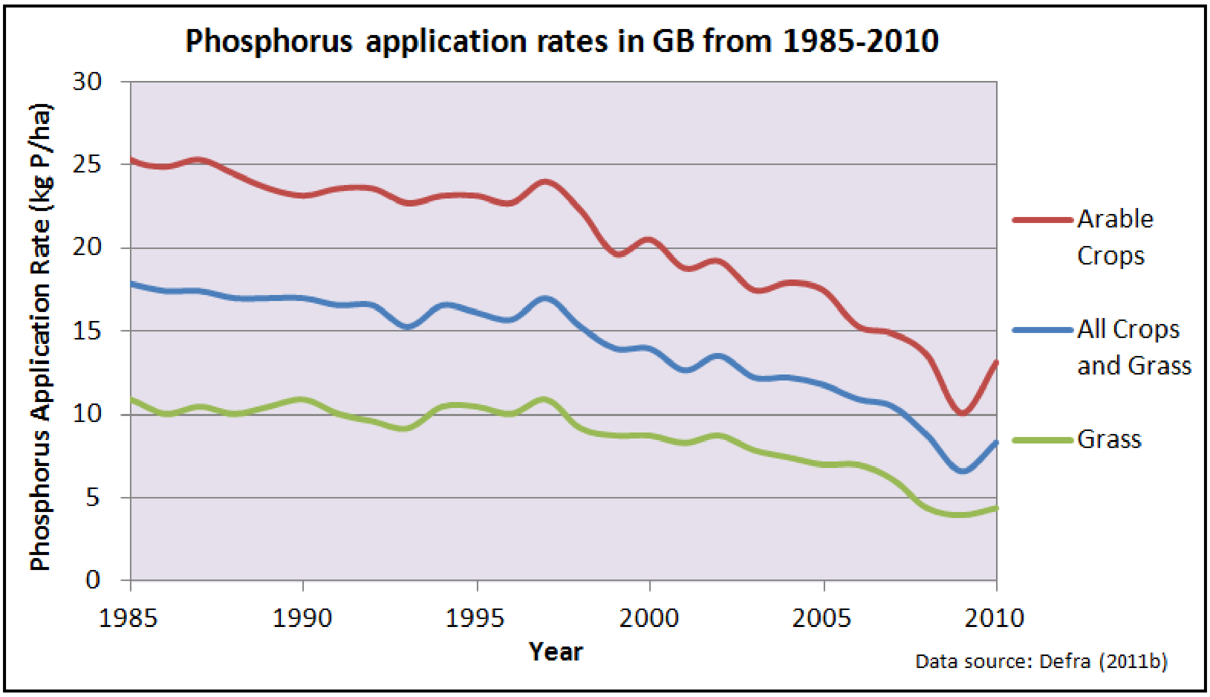


Figure 25: Phosphate application rates in Great Britain from 1985 to 2010.
Data source: Defra (2011b)

An additional issue not reflected within this SFA is the variation within a single year. The data presented within this analysis represents the whole year, whereas for some phosphorus flows, such as phosphorus within harvested crops, there are clear variations throughout the year. Bateman et al. (2011) demonstrated a temporal mismatch between housed organic manure production and the demand for fertiliser in the UK, suggesting that recycling would require significant storage capacity during times of low demand. The production of sewage sludge from the water industry is relatively constant throughout the year, and there are clear guidelines set out in the Code of Practice for Agriculture use of sewage sludge for the safe handling, storage and application of sewage sludge.

This SFA produces an overall picture of the UK system, but doesn't take into account regional variations. These variations are important considering the decoupled nature of food production and consumption, the decoupled nature of arable and animal farming, and also the bulky nature of wastes, such as manure and sewage sludge, which currently makes transport expensive and therefore limits the options for effective recycling. Bateman et al. (2011) demonstrated that livestock production and the resulting organic fertiliser production occurs mostly in the west of the UK, while arable land and the demand for fertilisers occurs largely in the east of the country. This geographical issue has been overcome in this thesis for the water industry by analysing data collected from each individual water company (Section 6.1), therefore enabling phosphorus flows in the whole of the UK water industry to be split up into individual companies and their corresponding regions. This data could be used to develop regional-scale SFAs, although this way beyond the scope of this thesis.

Finally, since the SFA focuses entirely on the quantity of the element within each flow, it does not consider the properties of the material, such as phosphorus concentration, water content, additional nutrients and contaminants. These properties could affect the suitability of a material for recycling. This analysis was also beyond the scope of this thesis for products being produced from the water industry. However, the properties of sewage sludge and other fertiliser products produced from wastewater are highly regulated to ensure the safety of their use.

Despite some of these limitations, the results of the SFA remain useful for the purposes of this thesis. The UK remains an overall net importer of phosphorus, meaning that it is vulnerable to global scarcity. Also, the water industry is revealed as a key stakeholder in the overall phosphorus flows through the UK food production and consumption system. Since the industry also contributes the largest amount of phosphorus to UK waters, this suggests that the water industry would be targeted to remove and recycle increasing amounts of phosphorus to improve UK phosphorus security and whilst increasing the quality of UK waters.

6.3 Reserve-to-production ratio analysis

The global reserve-to-production (R/P) ratio estimates that phosphate rock reserves could last for around 370 years at current extraction rates. However, global phosphate rock reserves are made up of individual deposits found within individual countries, and these countries operate different R/P ratios. The global R/P ratio is highly influenced by Morocco, which has an R/P ratio of nearly 2,000 years. Without Morocco, the global R/P ratio reduces to around 100 years.

The analysis undertaken as part of this research was designed to investigate how the distribution of phosphate rock reserves and share of supply may change throughout the 21st Century as a result of the different reserve-to-production (R/P) ratios that are currently being operated within individual countries. This involved the development of 3 different scenarios and a number of assumptions, as outlined in the Methodology (Section 5.3). This section will present the results from these three scenarios, which formed the basis for the paper produced by Cooper et al. (2011) (Appendix A).

6.3.1 Depleting reserves and declining production

The first scenario investigates how depletion of reserves in certain countries will affect global production. At current production rates, many countries will have depleted their existing reserves before the end of the century. As suggested in USGS 2011 phosphate rock reserve estimates, only 7 countries in the world will have any reserves remaining by the year 2100. The depletion of these reserves prevents any further production from these countries. Therefore, unless production is increased in other countries, global production will be reduced in the future, as shown in Figure 26. China and the USA currently produce over half of the world’s phosphate rock production, and these reserves will be depleted in less than 60 years at constant extraction rates. Furthermore, around 70% of global production is currently produced from reserves which will be depleted within 100 years. Therefore, simply maintaining global phosphate rock production throughout the 21st Century will involve substantial increases in production within some countries to compensate for depleting reserves and lost production in others.

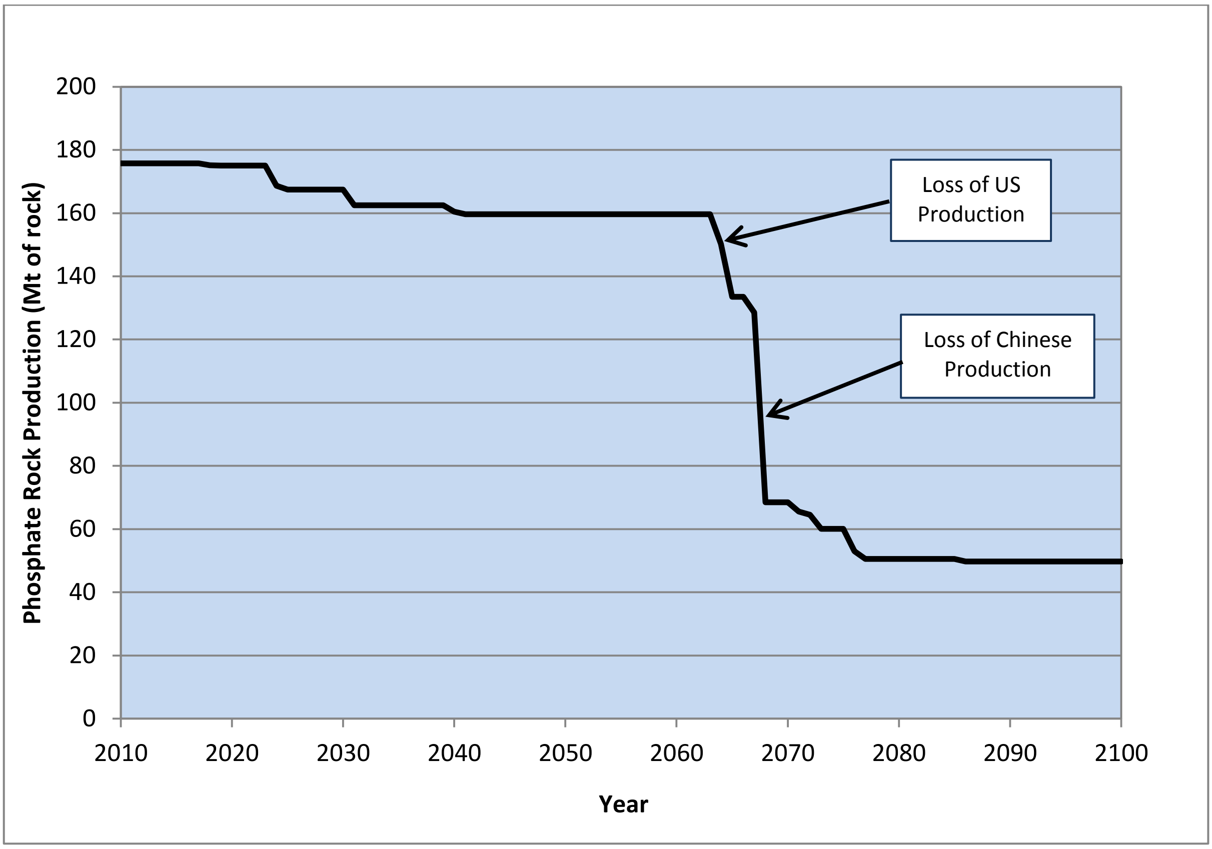


Figure 26: Future global phosphate rock production if individual countries maintain current levels of production.

6.3.2 Production Deficit

The second scenario was developed to determine how large a future production deficit may be as a result of increased demand and declining production. As stated in Section 4.3.5, the demand for food, feed, fertiliser and phosphorus will increase in the future, putting additional pressure to increase global phosphate rock production beyond that which will be required to maintain constant production levels. In this analysis, the demand for phosphate rock is assumed to increase by 1% per year between 2010 and 2050, and then remain constant between 2050 and 2100. This is shown in Figure 27, along with the resulting production deficit which arises from the increasing demand and depleting supply from the first scenario. By 2070 the production deficit is estimated to be over 200 Mt, which is larger than current production.

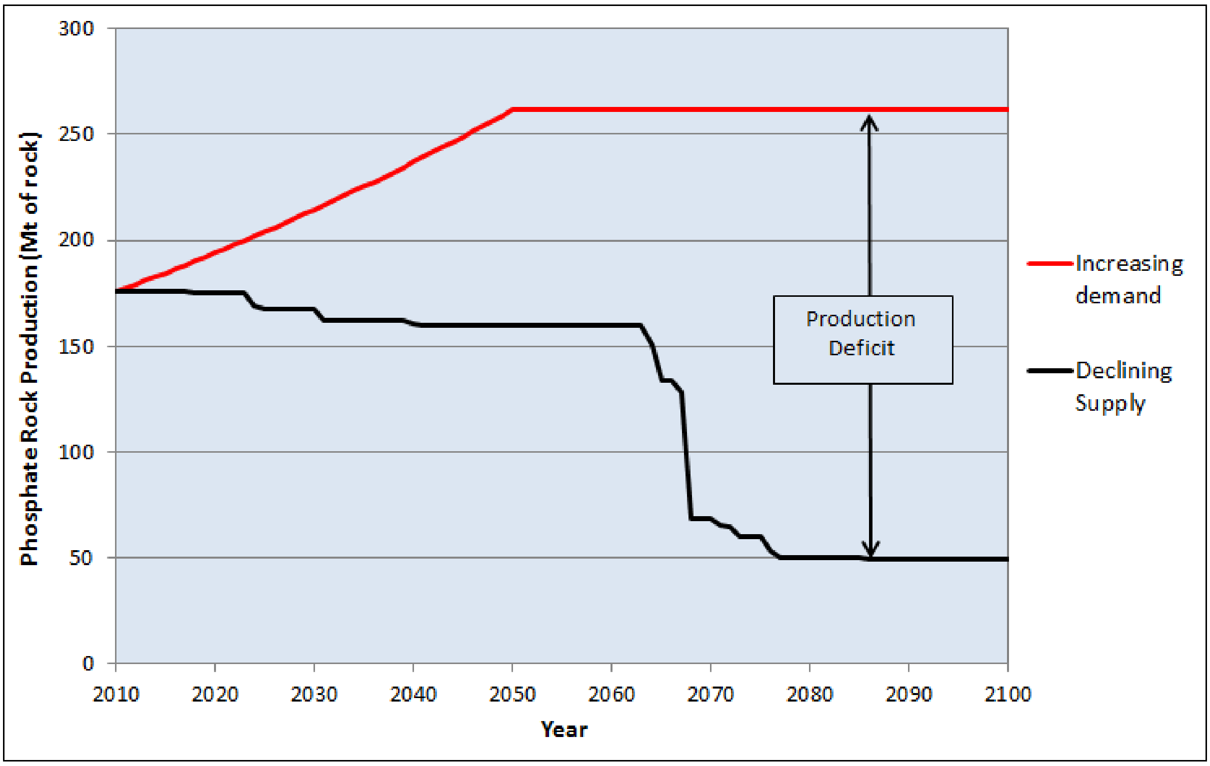


Figure 27: The growing production deficit for global phosphate rock reserves throughout the 21st Century as a result of depletion of reserves within individual countries and an increasing global demand for phosphate rock.

6.3.3 The Future Distribution of Reserves and Production

The third scenario was developed to determine how increased production can be achieved in some countries to prevent the production deficit highlighted in the second scenario, and how these production increases in certain countries will shape the future phosphorus supply landscape throughout the 21st Century.

Phosphate rock production will have to increase within some countries to meet the deficit that results from depleting reserves and increasing demand. This fact was noted in the IFDC report that production from Florida, USA, will be replaced by Morocco and other countries at an indeterminate time in the future (Van Kauwenbergh, 2010). It is assumed that the increase in production from individual countries will be proportional to the size of the remaining reserves within that country. Therefore Morocco, which has significantly larger reserves than any other country, is expected to increase production more than any other country. Figure 28 demonstrates how future demand would be met if production was increased within the remaining phosphorus-producing countries based on the assumption outlined in Section 5.3.

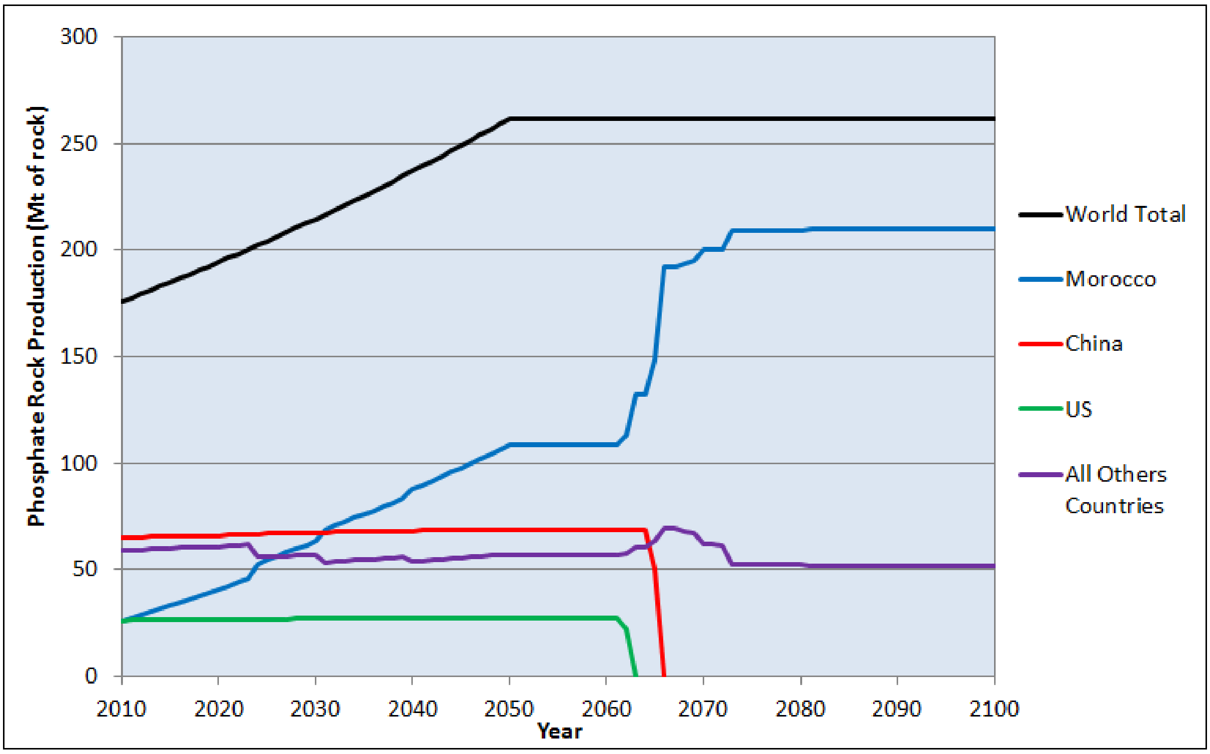


Figure 28: Changing phosphate rock production within individual countries to meet the projected global demand.

Source: Cooper et al. (2011) (Appendix A).

As can be seen in Figure 28, Morocco's production will need to increase significantly (by around 700% by 2075) in order to meet most of the future production deficit. This increase will result in phosphate rock production from Morocco exceeding 200 Mt/year, which is greater than global production in 2010 (176 Mt). The analysis shows that the trend for future production is to become more concentrated than it is today, as shown in Figure 29, with Morocco responsible for over 20% of global production by 2020, over 40% by 2050 and around 80% by 2100. This will give Morocco significant control of global production and also increasing control over the market price of phosphate rock in the future.

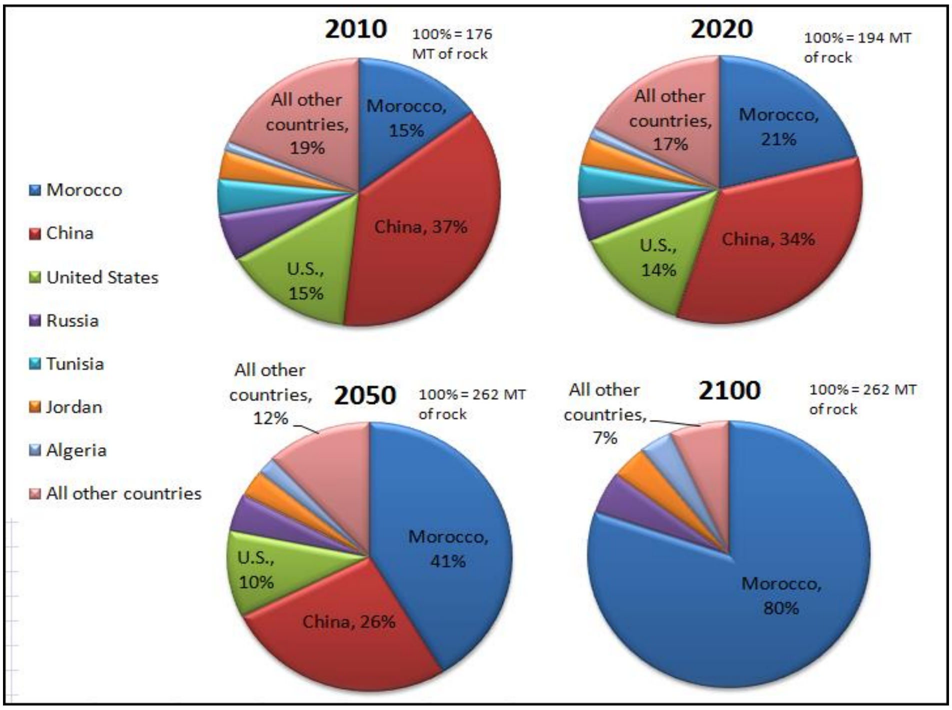


Figure 29: The changing share of phosphate rock production.
Source: Cooper et al. (2011) (Appendix A).

Also, since Morocco starts and ends the analysis with the highest R/P ratio, then proportionally it is depleting its reserves slower than the other countries, meaning that, despite the massive increases in production, its share of the global reserves will continue to increase, as shown in Figure 30.

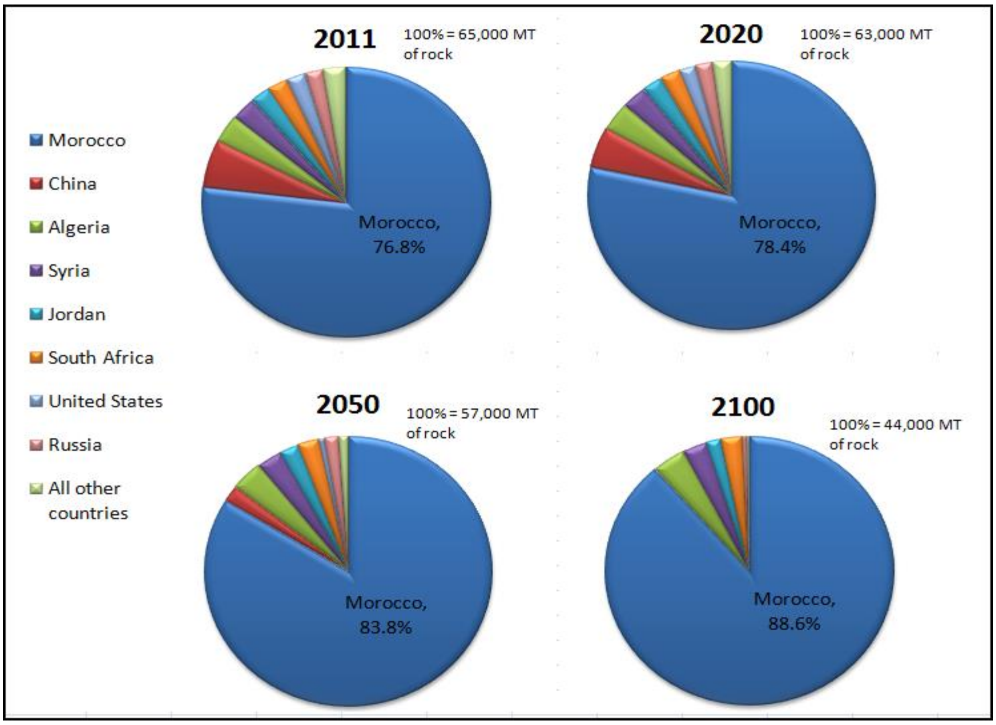


Figure 30: The changing distribution of phosphate rock reserves.
Source: Cooper et al. (2011) (Appendix A).

6.3.3.1 Limitations to the analysis using reserve-to-production ratios

The analysis presents the possibility of a future phosphate rock production deficit, suggests how this deficit might be met and analyses how this would affect the distribution of reserves and share of production. To simplify the analysis, a number of key assumptions were implemented (see Section 5.3) which should be considered when interpreting these results. Indeed, is not intended that exact figures be drawn from this analysis, but instead that the overall trends are considered:

- The demand for phosphate rock will increase.
- The current reserves owned by the U.S. and China will be mostly or completely depleted this century, and with them around half of world's current phosphate rock production.

- Replacement production will occur mostly in Morocco, the only country with reserves large enough to sustain such production levels. Therefore, Morocco will obtain a much greater share of global production.
- Morocco has the highest R/P ratio, currently at around 2,000 years, which is much higher than the world average of 370 years. Despite increased production, Morocco will continue to operate a large R/P ratio in the future and will therefore end with an even greater share of global reserves by the end of the Century.

6.4 Analysis of the Phosphorus Recycling Obligation scheme

Increased recycling of phosphorus from wastewater is likely to form a crucial part of a UK-wide strategy to increase the security of phosphorus supplies. The section sets out how the water industry would respond to the Phosphorus Recycling Obligation (PRO) scheme, which was developed for this research, and if the investments outlined in the methodology (Section 5.4.4) would be sufficient to achieve the phosphorus recycling targets established in Section 5.4.2, including the 80% phosphorus recycling target by 2050. Three scenarios were established (2012, 2025 and 2050) and this section presents the results from the analysis of each in turn.

6.4.1 The current performance

The first scenario was developed to determine how the industry would perform if the PRO scheme was already in operation. The year 2012 was chosen as the year for which the data about the industry (from Section 6.1) was correct. The industry-wide target was set at 44% (see Table 13) and the assumptions for this scenario are established in the methodology (Section 5.4.4).

The performance indicators for the industry as a whole are presented in Table 28, and show that the industry currently recycles 47.3% of the total phosphorus load to UK WwTWs. This exceeds the 44% target for 2012.

Table 28: Performance indicators for the water industry in 2012

Performance parameter	Value in 2012	Unit
1. Amount of P entering UK WwTWs	56.3	kt P/year
2. Amount of P in final effluent	23.4	kt P/year
3. P removal efficiency	58.5	%
4. Amount of P in sewage sludge recycled to agricultural and non-agricultural land.	26.6	kt P/year
5. Amount of P recovered from wastewater (e.g. struvite)	0.0	kt P/year
6. Amount of P recovered from thermal destruction processes.	0.0	kt P/year
7. Total amount of P recovered or recycled from wastewater	26.6	kt P/year
8. Percentage of P recycled from wastewater	47.3	%

As shown in Figure 31, UK wastewater treatment works removed 58.5% of the 56.3 kt P that entered these works in 2012. Assuming that wastewater effluent will not be used for irrigation purposes, the maximum amount of phosphorus that could have been recycled in 2012 was therefore 58.5% of the total influent. This demonstrates that increased phosphorus removal will be an essential requirement of meeting greater recycling targets in the future, such as the 80% phosphorus recycling target by 2050.

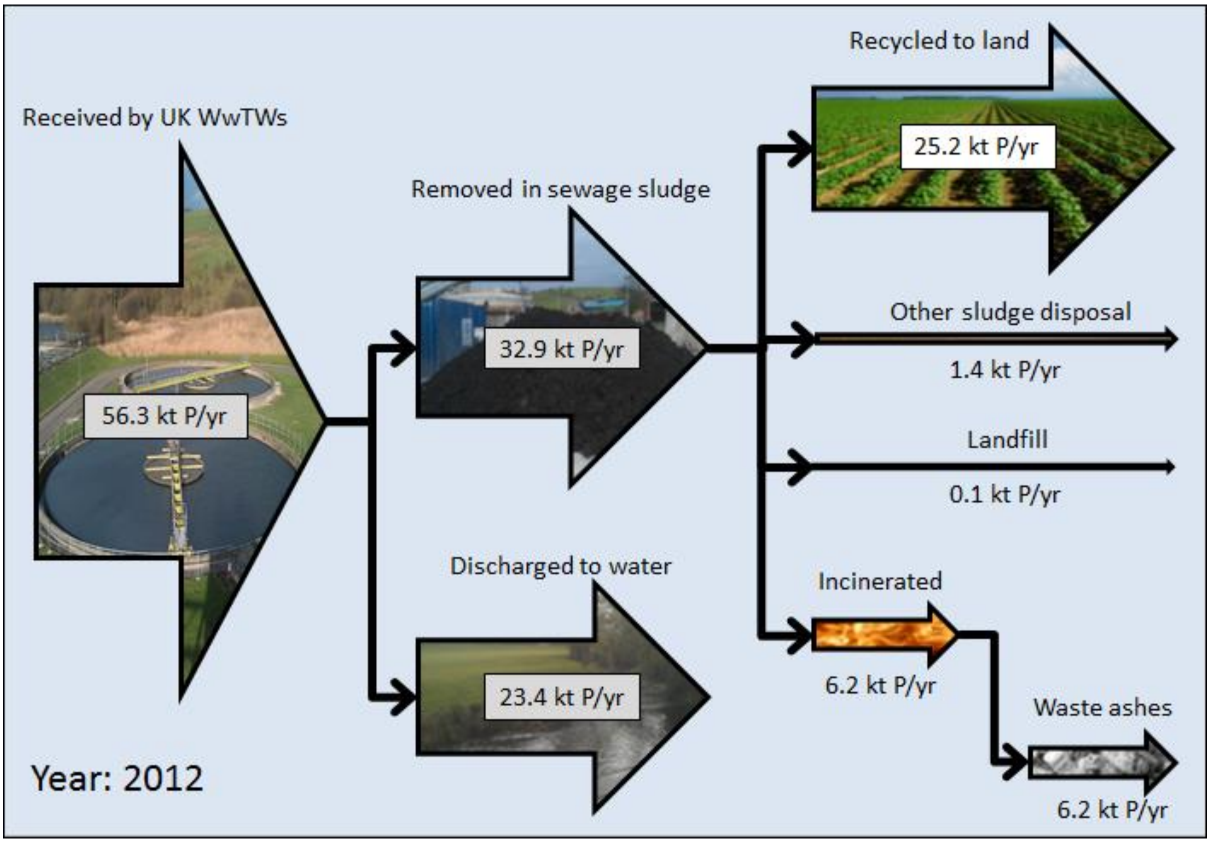


Figure 31: Phosphorus flows through the water industry in 2012

Approximately 32.9 kt P was removed within sewage sludge, and around 76% of this was recycled to agricultural land, containing 25.2 kt P. As of 2012, there were no phosphorus recovery facilities at UK wastewater treatment works; therefore recovered phosphorus was not included in Figure 31. However, in November 2013, Thames Water opened the first struvite recovery process at Slough STW (BBC News, 2013). Approximately 6.2 kt P within the sewage sludge was sent to incineration plants, and none of the phosphorus was recovered. Therefore, the primary method of recycling was achieved through recycling sewage sludge to agricultural land for food crops (25 kt P) and recycling to other land (1.7 kt P). In total, it is estimated that 26.6 kt P was recycled in 2012, which represents 47.3% of the total phosphorus load.

6.4.1.1 Performance by individual water companies in 2012

The industry as a whole met the 44% phosphorus recycling target. This section presents the results from the individual water companies, and how this would have functioned under the Phosphorus Recycling Obligation (PRO) scheme developed in the methodology (Section 5.4.3). Table 29 shows the estimated phosphorus loads and removal performance for each of the UK water companies. As can be seen, the phosphorus loads and removal performances vary significantly between each company. These results reveal that companies such as Southern Water and Yorkshire Water, which have low levels of phosphorus removal (around 50%), would have to recycle almost 100% of the phosphorus removed to meet the recycling targets. The results also suggest that companies such as Severn Trent, which removes 70.6% of the phosphorus, would be able to benefit greater from the PRO scheme if it could recycle all of the phosphorus in its sewage sludge.

Table 29: Phosphorus loads, removal performance and Phosphorus Recycling Obligation Certificates required in 2012

Water company	P load in 2012 (kt P/yr)	PROCs required (million)	P removed from influent (kt P/yr)	Average P removal performance (%)
Anglian Water	5.3	2.3	3.5	65.2
Northern Ireland	1.5	0.6	0.8	57.2
Northumbrian Water	2.4	1.1	1.3	53.2
Scottish Water	5.3	2.3	2.7	51.4
Severn Trent	7.9	3.5	5.6	70.6
South West	1.4	0.6	0.7	51.4
Southern Water	3.7	1.6	1.8	50.3
Thames Water	11.7	5.2	7.2	61.7
United Utilities	6.6	2.9	3.7	56.3
Welsh Water	3.1	1.4	1.6	53.1
Wessex Water	2.6	1.1	1.4	56.0
Yorkshire Water	4.8	2.1	2.4	50.5
Total	**56.3**	**24.8**	**32.9**	**58.5**

Table 30 presents the recycling routes for the individual water companies. The most dominant route for recycling is to recycle sewage sludge to agricultural land, either directly or following composting treatment. The results show that there is a large difference between the recycling performances of the water companies. Northern Ireland incinerates all of its sewage sludge, and therefore, without any phosphorus recovery processes, it is assumed that none of the phosphorus load is recycled. This also affects the performance of Thames Water, which also incinerates a large proportion of its sewage sludge. Severn Trent performs the best in this analysis, with a combination of high phosphorus removal rates and 100% sludge recycled to land.

Table 30: Phosphorus recycling routes in 2012

Water company	P recycled to agricultural land (kt P/yr)	P recycled to non-agricultural land (kt P/yr)	P recovered from wastewater (kt P/yr)	P recovered from incineration ashes (kt P/yr)	Total P recycled (kt P/yr)	Total P load recycled (%)
Anglian Water	3.3	0.2	0.0	0.0	3.5	65.2
Northern Ireland	0.0	0.0	0.0	0.0	0.0	0.0
Northumbrian Water	1.1	0.1	0.0	0.0	1.3	52.0
Scottish Water	1.4	0.0	0.0	0.0	1.4	25.7
Severn Trent	5.6	0.0	0.0	0.0	5.6	70.6
South West	0.5	0.1	0.0	0.0	0.7	51.4
Southern Water	1.8	0.0	0.0	0.0	1.8	50.3
Thames Water	4.0	0.5	0.0	0.0	4.4	37.9
United Utilities	3.5	0.0	0.0	0.0	3.5	52.9
Welsh Water	1.6	0.0	0.0	0.0	1.6	53.1
Wessex Water	1.4	0.0	0.0	0.0	1.4	54.7
Yorkshire Water	0.9	0.5	0.0	0.0	1.4	28.8
Total	**25.2**	**1.4**	**0.0**	**0.0**	**26.6**	**47.3**

Table 31 establishes how the companies would perform if the PRO scheme were in operation in 2012. It is assumed that all recycling activities receive 1 PROC, therefore the PROCs required in Table 29 can be compared to the PROCs generated from total recycling activities in Table 30 to calculate the surplus number of PROCs generated for each water company, as shown in Table 31. The water companies would submit a report of recycling activities to Ofwat each month, and receive a number of PROCs for these activities. It is assumed that the buy-out fee, trading value and surplus fee are £1.00, £0.75 and £0.50 respectively. The ability to trade PROCs is designed to encourage investments in the areas where phosphorus recycling is most cost-effective, and it is assumed that companies buy and sell PROCs in proportion to the size of their surplus or deficit.

As can be seen, the industry exceeds the phosphorus recycling target; therefore there is an overall surplus of PROCs. Only four water companies did not exceed their phosphorus recycling targets. Severn Trent benefits most from the PRO scheme in 2012, being able to trade 1.3 million PROCs at a value of £989,776 and receiving a surplus fee of £395,280 for the remaining PROCs, therefore generating a total revenue of £1.4 million. In this analysis, Scottish Water must buy the most PROCs, at a cost of £728,233. Overall, the surplus fees required would amount to £919,464. This money would be generated from an industry-wide tax based on the size of the individual water company.

Table 31: Performance in the Phosphorus Recycling Obligation scheme in 2012

Water company	Surplus PROCs	PROCs sold to other companies	Trading revenue (£)	Value of remaining PROCs (£)	Total revenue generated (£)
Anglian Water	1,129,703	706,219	529,664	211,742	741,406
Northern Ireland	-645,026	-645,026	-483,770	0	-483,770
Northumbrian Water	192,265	120,192	90,144	36,037	126,181
Scottish Water	-970,977	-970,977	-728,233	0	-728,233
Severn Trent	2,108,928	1,318,369	988,776	395,280	1,384,056
South West	99,636	62,286	46,715	18,675	65,390
Southern Water	229,549	143,500	107,625	43,025	150,649
Thames Water	-711,212	-711,212	-533,409	0	-533,409
United Utilities	588,686	368,009	276,007	110,338	386,345
Welsh Water	280,962	175,640	131,730	52,661	184,391
Wessex Water	275,873	172,458	129,344	51,707	181,051
Yorkshire Water	-739,458	-739,458	-554,593	0	-554,593
Total	**1,838,929**	**0**	**0**	**919,464**	**919,464**

6.4.2 Meeting the 2025 target

The second scenario was developed to determine how the industry would perform if the PRO scheme was in operation in 2025. The recycling target was set at 55% (see Table 13) and the assumptions for this scenario are established in the methodology (Section 5.4.4).

The water industry's performance based on the assumptions outlined in the methodology is presented in Table 32. The results show that the industry would exceed the phosphorus recycling target, recycling almost 62% of the phosphorus load that entered all UK WwTWs.

Table 32: Performance indicators for the water industry in 2025

Performance parameter	Value in 2025	Unit
1. Amount of P entering UK WwTWs	61.2	kt P/year
2. Amount of P in final effluent	14.9	kt P/year
3. P removal efficiency	75.6	%
4. Amount of P in sewage sludge recycled to agricultural and non-agricultural land.	33.9	kt P/year
5. Amount of P recovered from wastewater (e.g. struvite)	3.9	kt P/year
6. Amount of P recovered from thermal destruction processes.	0.0	kt P/year
7. Total amount of P recovered or recycled from wastewater	37.8	kt P/year
8. Percentage of P recycled from wastewater	61.8	%

As shown in Figure 32, the total phosphorus load is expected to increase, estimated at 61.2 kt P/yr compared to 56.3 kt P in 2012. The increased level of phosphorus removal, including tertiary treatment at all works above 100,000 p.e. and ultra-treatment at all works with phosphorus consents in 2012, results in a significant increase in phosphorus removed from wastewater: 75.6% in 2025 compared to 58.5% in 2012. Despite increased phosphorus loads, the phosphorus flows in the final effluent would reduce from 23.4 kt P in 2012 to 14.9 kt P in 2025. It is assumed that a number of works with optimum conditions for phosphorus recovery from wastewater will have installed phosphorus recovery processes, and this would lead to 3.9 kt P being recovered from wastewater. The amount of sludge being incinerated is assumed to increase, but no phosphorus recovery processes for incineration ashes will be in place by 2025. Recycling sewage sludge to land is revealed to remain as the primary method of phosphorus recycling, and is expected to increase from 26.6 kt P in 2012 to 33.9 kt P in 2025. Overall, it is estimated that 37.8 kt P will be recycled in 2025, compared to 26.6 kt in 2012, which represents 61.8% of the phosphorus load and clearly exceeds the 2025 target of 55%.

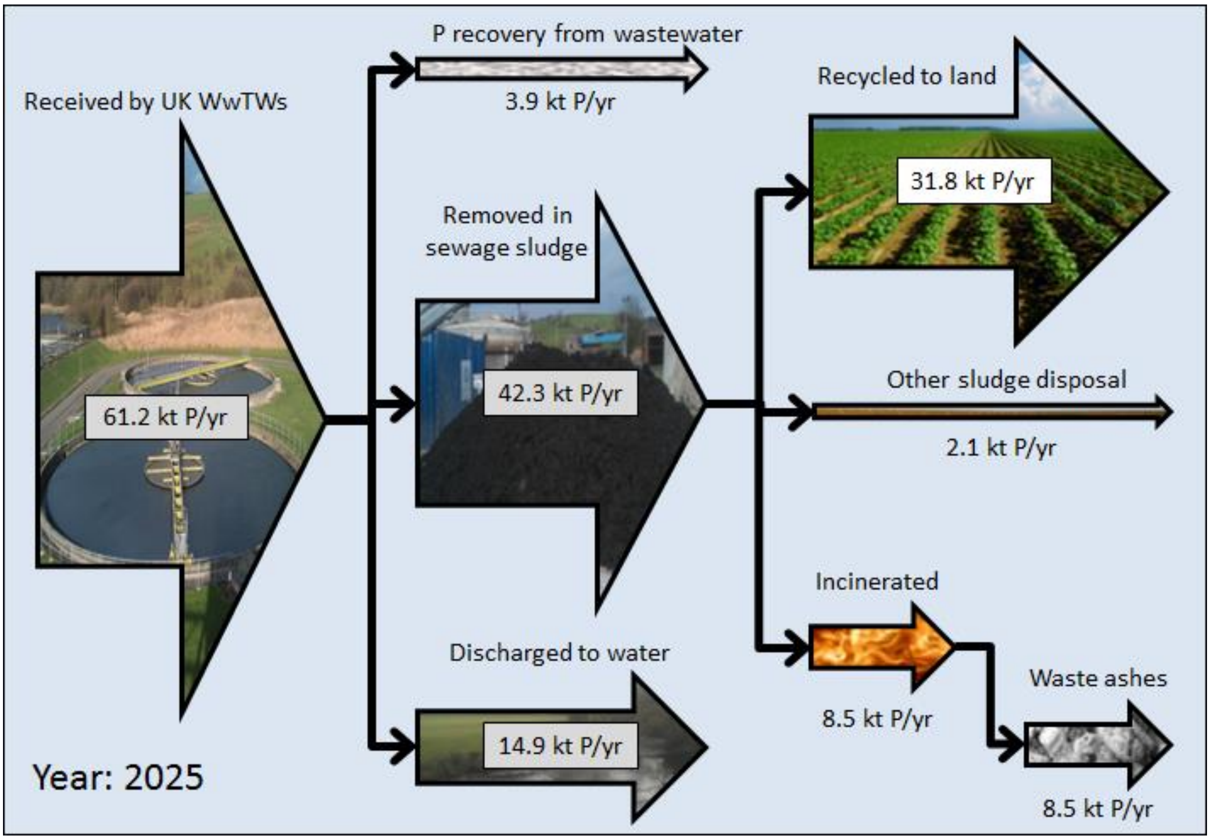


Figure 32: Phosphorus flows through the water industry in 2025

6.4.2.1 Performance by individual water companies in 2025

The results revealed that the industry was easily able to meet the 55% phosphorus recycling target for 2025. This section presents the individual contributions from the 12 UK water companies, and how they would perform under the PRO scheme.

Table 33 reveals that the phosphorus removal performance will have increased considerably across all water companies. Compared to 2012, where several companies were achieving phosphorus removal rates equivalent to the phosphorus recycling target, these results suggest that only South West Water is removing phosphorus equivalent to the 55% phosphorus recycling target. This suggests that all other companies would benefit from the PRO scheme if they could recycle the phosphorus that is removed.

The phosphorus removal performance of several companies, such as Thames Water, Northumbrian Water and Southern Water would increase considerably, since they operate a significant number of large WwTWs that do not have phosphorus consents in 2012, but are assumed to have installed phosphorus removal processes by 2025.

Table 33: Phosphorus loads, removal performance and Phosphorus Recycling Obligation Certificates required in 2025

Water company	P load in 2012 (kt P/yr)	PROCs required (million)	P removed from influent (kt P/yr)	Average P removal performance (%)
Anglian Water	5.8	3.2	4.5	77.2
Northern Ireland	1.6	0.9	1.1	68.7
Northumbrian Water	2.6	1.4	1.9	74.1
Scottish Water	5.8	3.2	4.0	69.2
Severn Trent	8.6	4.7	7.3	84.3
South West	1.5	0.8	0.8	56.5
Southern Water	4.0	2.2	2.6	65.7
Thames Water	12.7	7.0	10.8	84.6
United Utilities	7.2	4.0	5.3	73.9
Welsh Water	3.3	1.8	2.4	70.7
Wessex Water	2.8	1.5	2.0	70.7
Yorkshire Water	5.3	2.9	3.6	68.9
Total	**61.2**	**33.6**	**46.2**	**75.6**

It is assumed that most sewage sludge disposal routes will remain the same in 2025 as in 2012, except for all sewage sludge that was disposed of to landfill 2012 will be used on non-agricultural land in 2025. A number of companies have WwTWs with optimum conditions for phosphorus recovery technologies, and it is assumed that these will be installed by 2025. Under these assumptions, Northern Ireland would recover 0.04 kt P from wastewater, while Severn Trent would recover 1.6 kt P/yr. Despite clearly exceeding the industry phosphorus recycling target, three companies would fail to reach their individual targets.

Table 34: Phosphorus recycling routes in 2025

Water company	P recycled to agricultural land (kt P/yr)	P recycled to non-agricultural land (kt P/yr)	P recovered from wastewater (kt P/yr)	P recovered from incineration ashes (kt P/yr)	Total P recycled (kt P/yr)	Total P load recycled (%)
Anglian Water	3.7	0.2	0.5	0.0	4.5	77.2
Northern Ireland	0.0	0.0	0.04	0.0	0.0	2.3
Northumbrian Water	1.7	0.2	0.0	0.0	1.9	74.1
Scottish Water	2.0	0.0	0.0	0.0	2.0	34.9
Severn Trent	5.7	0.0	1.6	0.0	7.3	84.3
South West	0.7	0.2	0.0	0.0	0.8	56.5
Southern Water	2.6	0.0	0.0	0.0	2.6	65.7
Thames Water	5.2	0.6	1.3	0.0	7.1	56.1
United Utilities	4.7	0.0	0.3	0.0	5.0	69.7
Welsh Water	2.3	0.1	0.0	0.0	2.4	70.7
Wessex Water	1.9	0.0	0.0	0.0	2.0	70.7
Yorkshire Water	1.4	0.8	0.0	0.0	2.1	40.3
Total	**31.8**	**2.1**	**3.9**	**0.0**	**37.8**	**61.8**

Under the PRO scheme, three companies (Anglian, Severn Trent and Thames Water) would generate over 1 million surplus PROCs. A large proportion of these would be sold to the three companies with a deficit, and the remainder would be awarded the surplus fee. Overall, the surplus fee payments would exceed £2m.Severn Trent would again benefit most from the PRO scheme in 2025 under the assumptions made for this scenario.

Table 35: Performance in the Phosphorus Recycling Obligation scheme in 2025

Water company	Surplus PROCs	PROCs sold to other companies	Trading revenue (£)	Value of remaining PROCs (£)	Total revenue generated (£)
Anglian Water	1,285,380	514,580	385,935	385,400	771,335
Northern Ireland	-838,529	-838,529	-628,897	0	-628,897
Northumbrian Water	498,763	199,671	149,753	149,546	299,299
Scottish Water	-1,155,339	-1,155,339	-866,504	0	-866,504
Severn Trent	2,522,265	1,009,746	757,309	756,260	1,513,569
South West	22,682	9,080	6,810	6,801	13,611
Southern Water	424,933	170,115	127,586	127,409	254,995
Thames Water	137,039	54,861	41,146	41,089	82,235
United Utilities	1,056,098	422,791	317,093	316,654	633,746
Welsh Water	524,298	209,894	157,420	157,202	314,622
Wessex Water	440,206	176,229	132,172	131,989	264,160
Yorkshire Water	-773,099	-773,099	-579,824	0	-579,824
Total	**4,144,698**	**0**	**0**	**2,072,349**	**2,072,349**

6.4.3 Meeting the 2050 target

The third scenario was developed to determine if, based on the assumptions established in the methodology (Section 5.4.4), the water industry would meet the 80% phosphorus recycling target by 2050, and how the PRO scheme would impact the individual water companies.

The water industry's performance is presented in Table 36 and Figure 33. The results show that, despite large investments in phosphorus removal, and phosphorus recovery from wastewater and incineration ash, the industry would recycle 75.7% of the total phosphorus load, and therefore does not meet the industry target of 80% by 2050.

Table 36: Performance indicators for the water industry in 2050

Performance parameter	Value in 2050	Unit
1. Amount of P entering UK WwTWs	68.0	kt P/year
2. Amount of P in final effluent	7.5	kt P/year
3. P removal efficiency	89.0	%
4. Amount of P in sewage sludge recycled to agricultural and non-agricultural land.	21.2	kt P/year
5. Amount of P recovered from wastewater (e.g. struvite)	16.8	kt P/year
6. Amount of P recovered from thermal destruction processes.	13.5	kt P/year
7. Total amount of P recovered or recycled from wastewater	51.5	kt P/year
8. Percentage of P recycled from wastewater	75.7	%

As shown in Figure 33, the phosphorus load to UK WwTWs is expected to increase to 68.0 kt/yr by 2050. This is an 11% increase on the phosphorus load from 2025. The assumptions established in the methodology include large increases in phosphorus removal. In particular, it is assumed that tertiary treatment (achieving 80% phosphorus removal) is applied to all WwTWs >10,000 p.e., and ultra phosphorus removal (achieving 95% phosphorus removal) is applied to all WwTWs >100,000 p.e. and those that had phosphorus consents in 2012. With this large-scale investment in phosphorus removal technology, it is estimated that the industry would be able to remove 89% of the influent phosphorus. This quantity of phosphorus would be sufficient to meet the phosphorus recycling target if it could all be recycled. Therefore, the failure to meet the target is not due to insufficient phosphorus removal. Despite the large increases in phosphorus loads to WwTWs, this level of phosphorus removal would mean that final effluent discharges reduce in phosphorus content, from 23.4 kt in 2012 to 7.5 kt in 2050.

It is assumed that processes for recovering phosphorus from wastewater will be operating at all WwTWs >100,000 p.e., recovering 16.8 kt P/yr. Furthermore, it is assumed that phosphorus recovery processes treating incineration ashes have been installed and, combined with an increase in the amount of sludge being incinerated, would recover 13.5 kt P/yr from incineration ashes. With these assumptions, the amount of phosphorus recovered from wastewater and incineration ashes would be 30.5 kt P/yr, exceeding the 21.2 kt P recycled within sewage sludge. In total, it is estimated that 51.5 kt P/yr would be recycled by 2050, which is 75.7% of the estimated phosphorus load to the industry. The amount of phosphorus recycled would be double the amount currently recycled in 2012, although the 80% target would not be met with these assumptions.

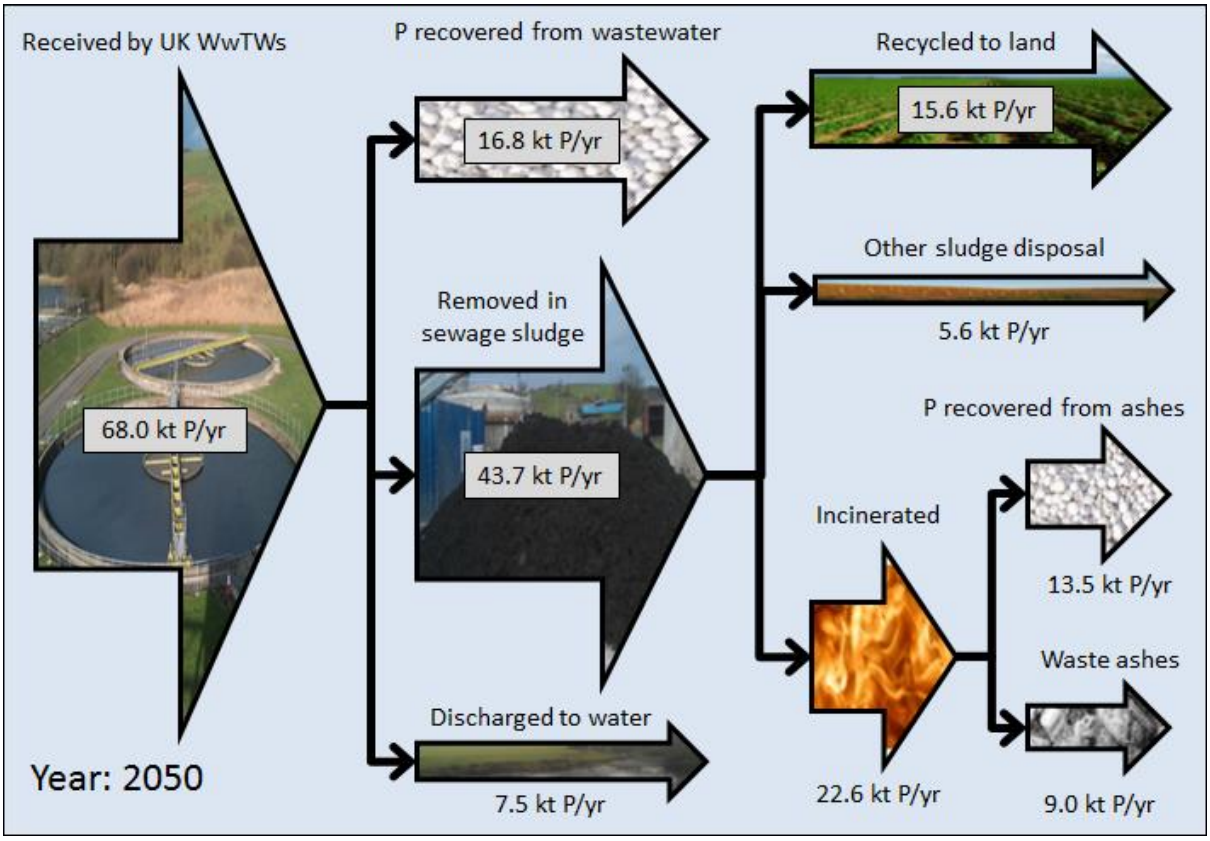


Figure 33: Phosphorus flows through the water industry in 2050

6.4.3.1 Performance by individual water companies in 2050

The results revealed that, despite large increases in phosphorus removal and phosphorus recovery, the industry would not be able to meet the 80% phosphorus recycling target for 2050 based on the assumptions set out in the methodology. This section presents the results for the individual UK water companies in 2050, and how they would have functioned under the PRO scheme.

Table 37 reveals that the phosphorus removal performance would increase considerably by 2050, with several companies, such as Severn Trent, Thames Water and United Utilities, exceeding 90% phosphorus removal. Only one company, South West Water, does not remove a sufficient quantity of phosphorus from wastewater to achieve the phosphorus recycling target, even if all of the removed phosphorus could be recycled.

Table 37: Phosphorus loads, removal performance and Phosphorus Recycling Obligation Certificates required in 2050

Water company	P load in 2050 (kt P/yr)	PROCs required (million)	P removed from influent (kt P/yr)	Average P removal performance (%)
Anglian Water	6.5	5.2	5.6	86.1
Northern Ireland	1.8	1.4	1.5	82.9
Northumbrian Water	2.9	2.3	2.6	89.8
Scottish Water	6.4	5.1	5.6	86.7
Severn Trent	9.6	7.7	8.7	90.3
South West	1.6	1.3	1.3	78.0
Southern Water	4.4	3.5	3.8	86.1
Thames Water	14.2	11.3	13.3	93.7
United Utilities	8.0	6.4	7.2	90.3
Welsh Water	3.7	3.0	3.2	86.5
Wessex Water	3.1	2.5	2.7	87.3
Yorkshire Water	5.9	4.7	5.2	88.5
Total	68.0	54.4	60.5	89.0

The disposal of sewage sludge to agricultural land is assumed to become more difficult by 2050. This is due to increased restrictions on sludge applications to land to protect human and environmental health. As defined in the methodology (Section 5.4.4), it is assumed that more sludge will be diverted to incineration or other thermal destruction technologies, or used on land to grow energy crops, both of which may support the companies' renewable energy and carbon reduction targets.

As presented in Table 38, the phosphorus recycling routes are expected to alter significantly by 2050. It is expected that much greater levels of phosphorus recovery will be occurring from both wastewater and incineration ashes, becoming roughly equivalent to sludge recycling to agricultural land. It is assumed that not all of the phosphorus is able to be recovered, particularly from incineration ashes, which results in many water companies not meeting their phosphorus recycling targets, despite the large amounts of phosphorus being removed from the influent shown in Table 37. Under these assumptions, only four companies (Northumbrian, Severn Trent, Welsh and Wessex Water) were able to meet the 80% phosphorus recycling target.

Table 38: Phosphorus recycling routes in 2050

Water company	P recycled to agricultural land (kt P/yr)	P recycled to non-agricultural land (kt P/yr)	P recovered from wastewater (kt P/yr)	P recovered from incineration ashes (kt P/yr)	Total P recycled (kt P/yr)	Total P load recycled (%)
Anglian Water	2.6	0.7	1.2	0.7	5.1	79.3
Northern Ireland	0.0	0.0	0.3	0.7	1.0	55.4
Northumbrian Water	1.1	0.3	0.7	0.3	2.4	83.3
Scottish Water	0.6	0.4	1.5	1.8	4.3	67.7
Severn Trent	4.1	0.6	2.3	0.9	8.0	83.7
South West	0.6	0.2	0.1	0.2	1.2	71.0
Southern Water	1.9	0.3	0.9	0.4	3.5	79.6
Thames Water	0.9	1.3	4.7	3.9	10.7	75.5
United Utilities	0.8	0.5	2.1	2.3	5.7	71.1
Welsh Water	1.6	0.2	0.8	0.4	3.0	80.1
Wessex Water	1.3	0.3	0.6	0.3	2.5	80.5
Yorkshire Water	0.2	0.7	1.5	1.7	4.1	69.6
Total	**15.6**	**5.6**	**16.8**	**13.5**	**51.5**	**75.7**

Overall, the industry would fail to meet the 80% phosphorus recycling target by 2050 based on these assumptions. This would result in an overall deficit of PROCs under the PRO scheme. Two companies, Scottish Water and United Utilities, would both have deficits of over 700,000 PROCs. With a limited number of surplus PROCs being generated by other companies, there would be limited capacity to buy PROCs from other companies, and these companies would have to pay the buy-out fee. Overall, the buy-out fee payments would exceed £2.9m. This money would be used to cover the costs of the scheme, pay any surplus fees and be invested into relevant research projects.

Table 39: Performance in the Phosphorus Recycling Obligation scheme in 2050

Water company	Surplus PROCs	PROCs sold to other companies	Trading revenue (£)	Value of remaining PROCs (£)	Total revenue generated (£)
Anglian Water	-42,405	-5,845	-4,384	-36,560	-40,944
Northern Ireland	-435,747	-60,066	-45,049	-375,681	-420,731
Northumbrian Water	95,354	95,354	71,515	0	71,515
Scottish Water	-786,012	-108,348	-81,261	-677,664	-758,925
Severn Trent	353,150	353,150	264,862	0	264,862
South West	-146,835	-20,240	-15,180	-126,594	-141,775
Southern Water	-19,852	-2,737	-2,052	-17,116	-19,168
Thames Water	-631,122	-86,997	-65,248	-544,125	-609,372
United Utilities	-710,770	-97,976	-73,482	-612,794	-686,276
Welsh Water	3,083	3,083	2,312	0	2,312
Wessex Water	14,437	14,437	10,828	0	10,828
Yorkshire Water	-608,039	-83,815	-62,861	-524,224	-587,085
Total	**-2,914,758**	**0**	**0**	**-2,914,758**	**-2,914,758**

7 DISCUSSION

The aim of this research was to determine if the UK water industry will be required to increase the amount of phosphorus that is recycled from wastewater in the future in order to address national resource security. This section discusses the results from the analyses that were conducted to address this research aim.

7.1 The current position of the UK water industry

The literature review revealed that the water industry currently manages phosphorus as a pollutant, although little information was available about the existing infrastructure. The analysis of this data, gathered from all 12 UK water companies about the existing infrastructure, was used to determine how compatible the existing infrastructure is with current phosphorus removal and recovery technologies, what the key obstacles for increased phosphorus recycling would be, and what contributions towards phosphorus recycling could be made from the individual water companies. This section discusses the significance of these results in terms of phosphorus management in the UK water industry to address resource security in the UK.

Increased phosphorus recycling from wastewater will require additional investments at UK WwTWs into technologies that remove and recover increased amounts of phosphorus. These technologies are expected to be more suitable and more economically feasible at the larger WwTWs, which generally receive greater phosphorus loads. The results presented in Section 6.1.1 (Table 21) suggest that if the technologies could only be applied at works with a p.e. >100,000, this is still around 60% of the total phosphorus within UK wastewater. If the processes could be implemented at all Band 6 works (>25,000), then this would access over 80% of the phosphorus within wastewater. This is encouraging for phosphorus recycling from wastewater in the UK.

There are now several full-scale processes for recovering phosphorus (either as struvite or calcium phosphate) from the liquid faction, but almost all of these require high concentrations of soluble phosphorus, and therefore EBPR (see Table 3). This is a potential barrier, as these results suggest that chemical phosphorus removal accounts for around 75% of all phosphorus removal processes in the UK. This is the legacy of a water industry that has traditionally managed phosphorus as a pollutant, rather than a resource. Increasing the phosphorus recovery potential would require the large works without phosphorus removal and those using chemical phosphorus removal methods to be converted to EBPR. This conversion is likely to be easiest and more cost-effective at works with existing AS processes and discharge consents. As shown in Figure 20, the installation of EBPR and phosphorus recovery at the larger WwTWs presents the greatest opportunity to increase the amount of phosphorus recovered as struvite. If back-up chemical dosing is required, separating chemical and biological sludges would be required to facilitate phosphorus recovery.

The increasing demand for phosphorus removal to meet WFD targets presents the opportunity to couple this with increased phosphorus recovery, which would address both the resource and pollutant aspects of phosphorus management. Increasing the level of phosphorus removal at WwTWs would also increase the amount of phosphorus available for recovery at the larger works, whilst making economic recovery more feasible at the smaller works. Increasing the release of phosphorus from sewage sludge and the efficiency of recovery processes would potentially allow more than 40% of the influent phosphorus to be recovered as struvite.

Phosphorus can also be recovered from the ashes of incineration or other thermal destruction processes. This would capture the phosphorus that remains in the sewage sludge, and is not available for recovery from the liquid phase. An advantage with this form of recovery is that very few phosphorus recovery plants would be required, since the ashes from several incinerators could be transported to a centralised plant and processed to recover the phosphorus. However, the potential for phosphorus recovery from incineration ashes is currently relatively low in the UK compared to recovery from the liquid phase, since only 18% of sewage sludge is sent for thermal destruction (Water UK, 2010). Furthermore, many of technologies that have been developed for phosphorus recovery from incineration ashes have specific requirements for the chemical composition of the ashes, which often includes a low Fe content. With increasing restriction on sludge to land practices, it is expected that thermal destruction methods will become increasingly favoured as a method of sewage sludge disposal. This will enable more phosphorus to be recovered from the ashes. Furthermore, if increasing numbers of works installed EBPR, or treated sludges separately, this would increase the potential for phosphorus recovery from incineration ash in the UK.

The water industry data presented in Section 6.1.4, demonstrates that there is a large difference between water companies in terms of the number and size of works, the treatment processes employed and the amount of phosphorus removal required. The geographical location of the companies also affects phosphorus removal requirements and the feasibility of recycling sewage sludge to agricultural land. Consequently, some companies will be able to recycle phosphorus more easily and make a larger contribution to phosphorus security in the UK than others. The results of the analysis suggest that due to the size and existing infrastructure, Thames Water and Severn Trent Water will be the companies that could contribute most to phosphorus recycling from the UK water industry. Due to the differences in infrastructure and ease of recycling between the water companies, it is suggested that a phosphorus recycling trading system should be implemented to encourage the most cost-effective investments within the water industry. .

As identified in the literature review (Section 4.1.1), the UK water industry currently has a significant size debt amounting to around £33 billion. Also, as identified in Section 4.1.2.3, the UK water industry must meet severe GHG emissions reductions under the carbon reduction commitment. Increasing the amount of phosphorus that is recycled from wastewater may require large investments at WwTWs, which could further increase the amount of debt held by the water companies and increase energy consumption. However, such an analysis is beyond the scope of this thesis.

The results from this analysis demonstrate that there is significant potential for increasing phosphorus recycling within the water industry, but that some significant barriers must be overcome to realise this potential. It is suggested that additional incentives or regulations will be required to increase phosphorus recycling within the water industry.

7.2 The substance flow analysis

Conducting a substance flow analysis is considered an essential step in developing a resource management system. The SFA conducted for this research quantified phosphorus flows throughout the UK food production system for the year 2009. The aim was to compare the amount of phosphorus within wastewater to other flows in the UK, in order to determine if the water industry is a key stakeholder in UK phosphorus management, and would therefore be targeted to increase phosphorus recycling in the future. The key results from this analysis are discussed within this section.

Firstly, the SFA revealed the extent to which the UK food production system relies on imported phosphorus. The UK has no domestic phosphate rock reserves, and therefore, like most European countries, is completely dependent on imports within food, feed and fertilisers. Total net imports amounted to 114.5 kt P/yr in 2009. The largest import was in mineral fertilisers, containing 77.5 kt P, which are required to support UK agriculture. In order to increase security of phosphorus supply, it is necessary to reduce the reliance on these imports. However, it may not be desirable to reduce imported food and feed products, as it is believed that food trade encourages increased agricultural efficiency and food security (Foresight, 2011). This is achieved by growing certain food types where it is most efficient to do so, and increasing resilience to regional disruptions, such as floods and droughts, through a diverse food supply. Therefore, increasing UK phosphorus security should focus primarily on reducing the demand for imported mineral fertilisers. The results from the SFA reveal that in a completely closed system where all wastes are recycled, there would be enough phosphorus within recycled materials to completely remove the need to import mineral fertilisers. If net imports of food and feed continued, there would even be a surplus of phosphorus, which would suggest that some of these wastes should be processed and exported, ideally back to the land producing food for the UK. This would increase phosphorus security for the whole UK food production system, which extends beyond the UK geographical boundaries.

The SFA revealed that the largest phosphorus flows in the UK are associated with agriculture. Applications of mineral fertilisers are estimated to contain 72.0 kt P/yr and animal manure is estimated to contain 167 kt P/yr. The efficiency of agricultural practices has been increased through best practice guidance and optimised applications of fertilisers to meet soil and crop requirements. As a result, overall mineral fertiliser applications have been reduced considerably from over 200.0 kt P/yr in 1970 to around 70.0 kt P/yr in 2009 (Defra, 2011b). However, the SFA results revealed the need to further increase use efficiency in agriculture to reduce over applications and diffuse pollution of water bodies. In particular, manure applications are believed to be responsible for most of the over applications, particularly in regions with intensive livestock production. A more effective utilisation of fertilisers and animal manures is required to reduce this over application, which would reduce the demand for imported mineral fertilisers and reduce the amount of phosphorus lost through diffuse pollution. This could be achieved through improved soil management to maintain optimum soil phosphorus levels, increased use of soil tests and precision applications of fertilisers, more effective distribution of animal manures where direct application is possible and further treatment of manures, including phosphorus recovery, where it is not.

The SFA identified the UK water industry as a key stakeholder in UK phosphorus management. In 2009, the water industry received approximately 55.0 kt P within wastewater and was responsible for the greatest losses from the system through final effluent discharges from WwTWs (23.5 kt P). These discharges to water bodies can cause eutrophication and result in failure to meet river quality objectives. Therefore, reducing phosphorus discharges within final effluent and increasing recycling could make a significant contribution to the quality of UK waters, while increasing UK phosphorus security.

The SFA results show that 57% of the phosphorus was removed from wastewater, estimated to contain 31.5 kt P. The UWWTD has resulted in increased phosphorus removal at UK WwTWs (Defra, 2002), and additional phosphorus removal will be required in the future to achieve the WFD targets (Environment Agency, 2012). It is estimated that WwTWs in Finland achieve 95% phosphorus removal from wastewater (Antikainen et al., 2005). If UK WwTWs removed 95% of the influent phosphorus, then the amount of phosphorus within final effluent would be reduced from 23.5 kt P/yr to just 2.8 kt P/yr. If the additional phosphorus that is removed from wastewater could then be recycled, this would make a significant contribution to UK phosphorus security.

Approximately 70% of the sludge was recycled to agricultural land, containing 22.5 kt P. This level of sewage sludge recycling has increased since the introduction of the UWWTD, which banned the disposal of sewage sludge to seas, and the Landfill Directive, which is aiming to reduce the amount of biodegradable waste sent to landfill through the use of a Landfill Tax. Sewage sludge applications were identified to be applying phosphorus at around 5 times greater than the uptake rate for crops. This demonstrates the challenges of effectively recycling bulky wastes. Furthermore, it is suggested that activities that apply phosphorus at rates that exceed crop requirements should not be considered as effective recycling. This is particularly important when considering phosphorus recycling targets for countries, industries or individual companies. The introduction of the Biosolids Nutrient Management Matrix in 2014 (see Section 4.1.4.1) means that sludge applications will have to take into consideration the soil phosphorus content (ADAS, 2013), which will improve recycling efficiency. Increasingly strict recycling regulations may also lead to the development of more effective methods of processing sewage sludge and other similar bulky wastes.

To ensure UK phosphorus security, there is going to be an increasing demand to recycle phosphorus from wastes. The results from the SFA have revealed that the UK water industry is a key stakeholder and will undoubtedly be required to play a role in a national phosphorus management system. Therefore, in addition to environmental protection, it is expected that the UK water industry will be required to increasingly manage phosphorus as a resource and increase recycling rates in the future.

7.3 The key driver for phosphorus scarcity

The literature review included a critical analysis of the key drivers for global scarcity that could affect phosphorus security in the UK. The aim of this analysis was to establish the timeframe within which the UK water industry may be required to increase the amount of phosphorus that is recycled from wastewater. The analysis revealed that the physical risks, such as absolute depletion of phosphate rock reserves or a peak in production, are now not expected to occur within the 21st Century, and that the geopolitical risks, generated by the concentration of phosphate rock reserves in a handful of countries, are the more pressing concern and are expected to be encountered within 50 years.

The purpose of the analysis undertaken for this thesis was to determine how this geopolitical situation might evolve in the future, and whether this influences the timeframe for increasing phosphorus recycling from wastewater. The analysis involved developing three scenarios for future phosphate rock supply and demand.

The first scenario investigated how global production would be affected if individual countries simply maintained current production levels. It was revealed that countries currently producing 70% of global phosphate rock production will deplete their reserves by the end of the 21st Century. The second scenario involved determining the combined effect of increasing demand and declining supply of phosphate rock. The results suggest that large increases in production would be required to meet the future production deficit. The greatest factor will the declining production within the US and China, which will occur before the 2070. Finally, the third scenario involved determining how this future production deficit would be met through increases in production within certain countries. The results suggest that Morocco will be supplying over 20% of global production by 2020, over 40% by 2050 and around 80% by 2100. However, the scale of production increases required in some countries, principally Morocco, to meet the projected future production deficit may not be possible. This may lead to a lag in phosphate rock production, or ‘lag phosphorus’, where global production continues to increase, so does not peak, but cannot keep pace with the increasing demand. This would create an increasing gap between supply and demand that would result in scarcity and price rises in the future. However, determining the future production capacity of Morocco is beyond the scope of this thesis.

These results demonstrate that the geopolitical risks to future phosphate rock supply will intensify throughout the 21st Century. This will reduce the timeframe within which to develop a more resilient phosphorus management system within the UK, which included phosphorus recycling from wastewater. And since such changes are likely to take many years to realise, it is suggested that the UK water industry will soon be required to begin managing phosphorus as a resource in an effort to increase phosphorus recycling and security of supply in the UK.

The following section discusses the strategy and phosphorus recycling targets that have been developed for this thesis as a means to initiate the change in phosphorus management within the UK water industry.

7.4 A resource management strategy

The literature review revealed that a number of countries have begun introducing national-scale phosphorus recycling targets, although little information is available concerning the strategies employed to achieve these targets, and no such targets have been established in the UK. Because of the many similarities between renewable energy and renewable phosphorus, the Phosphorus Recycling Obligation (PRO) was developed for this thesis following similar principles established for the Renewables Obligation (RO).

The purpose of the analysis was to determine if a series of phosphorus recycling targets could be achieved with specific improvements in phosphorus removal, recovery and recycling, and what impact this would have on national resource security. If increasing phosphorus recycling from wastewater is too expensive, and the impact on national resource security is too small, then this would suggest that the industry would not be required to increase phosphorus recycling in the future. The PRO scheme was developed for this analysis to provide the financial incentive for these specific investments to be made, and also to measure the impact on the individual water companies.

The basic principles of the PRO scheme involve setting individual phosphorus recycling targets to water companies and establishing a tradable quota system to ensure that long-term phosphorus recycling targets are met at the least possible cost. The overall target established is to recycle 80% of the phosphorus within wastewater by 2050, with an intermediate target of recycling 55% of phosphorus by 2025. A number of assumptions were developed concerning the investments made within the industry to meet these targets, which includes increased levels of phosphorus removal, phosphorus recovery from wastewater and incineration ashes, and changing sewage sludge disposal methods.

Within this analysis, all recycling activities were treated equally and received 1 PROC for each kg phosphorus recycled. Within the renewable energy obligation, the banding system was introduced to encourage investments in a diverse range of renewable energy technologies by awarding certain technologies more ROCs than others. This could be introduced in the PRO scheme to encourage alternative recycling activities, for example phosphorus recovered from the liquid phase could receive 2 PROCs, while direct recycling of sewage sludge receives 0.8 PROCs per kg phosphorus recycled. However, this decouples the number of PROCs with the amount of phosphorus recycled, and therefore companies could generate enough certificates without recycling a sufficient amount of phosphorus. A similar method would be to assign a % of phosphorus that is effectively recycled within a certain activity. For example, it could be considered that only 50% of the phosphorus applied to agricultural land is available to plants and effectively recycled; therefore 1 kg phosphorus applied within sewage sludge to agricultural land would only receive 0.5 PROCs. This method would ensure that 1 PROC is linked with 1 kg phosphorus that is effectively recycled. Finally, an alternative method of incentivising certain recycling technologies is to adjust the surplus fees received for PROCs based on the type of recycling that was undertaken. This could be organised with different categories for different phosphorus recycling practices, such as Category 1 PROCs. This mechanism is similar to a Feed-In Tariff scheme for low carbon energy, which awards different amounts of money to different technologies for each unit of energy produced. The overall phosphorus recycling target will still be controllable through the use of PROCs, although there would be different markets for trading different category PROCs. These different methods of banding could be explored further, but this was beyond the scope of this thesis, and instead the simplified assumption of treating all recycling activities equally was used.

The analysis demonstrated the importance of increased phosphorus removal to meet future phosphorus recycling targets. For example, it is estimated that in 2012 approximately 58.5% of the influent phosphorus was removed. This level of phosphorus removal would be insufficient to meet longer term targets, including the 80% phosphorus recycling target by 2050. Therefore, there exists a synergy with increasing phosphorus removal to meet phosphorus recycling targets and environmental objectives. This synergy would also help to reduce the costs of achieving phosphorus recycling targets. Unfortunately, there was insufficient information available to determine what level of phosphorus removal will be implemented in the future to meet river quality objectives, and hence whether additional phosphorus removal would be required to meet phosphorus recycling targets. As highlighted in Section 6.1.5, chemical phosphorus removal makes phosphorus recovery more difficult to achieve. The implementation of the PRO scheme would encourage water companies to invest in phosphorus removal technologies that ensure both objectives are achieved. This would likely result in increased levels of EBPR and separated stages for chemical phosphorus removal.

The phosphorus recycling target for the water industry for 2025 is proposed at 55%, and if the water industry makes the investments outlined in the methodology (Section 5.4.4), the amount of phosphorus recycled from wastewater would increase to 37.8 kt P/yr. This is 11.2 kt P/r greater than in 2012. The Roadmap to a Resource Efficient Europe proposes a milestone of reducing resource inputs to the food chain by 20% by 2020 (EC, 2011). Assuming mineral fertiliser applications in 2020 will be similar to 2009, this would require 14.4 kt P/yr to be substituted with renewable sources of phosphorus or reduced through efficiency gains in agriculture. If the additional 11.2 kt P/yr recycled from wastewater by 2025 was used to directly substitute mineral fertilisers, this would provide most of the phosphorus (77%) required to reduce resource inputs to agriculture by 20%. This suggests that increased recycling of phosphorus from wastewater would make a significant contribution to achieving this target and increasing UK phosphorus security.

In the 2050 scenario, it was estimated that the phosphorus load to WwTWs would increase to 68 kt P/yr and the level of phosphorus recycling would increase to 75.7%. This would result in 51.5 kt P being recycled from wastewater, which is almost double the amount of phosphorus that was recycled from wastewater in 2012.To achieve this, it was assumed that around 40% of the phosphorus removed from WwTWs >100,000 will be recovered from the liquid phase. This would involve all of these works being converted to EBPR and investing in phosphorus recovery facilities. The phosphorus that is recycled within sewage sludge, either directly or after processing, to agricultural and non-agricultural land is assumed to be completely recycled. Furthermore, an increasing amount of sewage sludge is expected to undergo some form of thermal destruction, including incineration, in the future as sludge to land recycling practices become more restricted. However, it was assumed that only 60% of the total phosphorus in incineration ash could be recovered, due to the combined factors of some ash being unsuitable for the phosphorus recovery process and the recovery performance being less than 100% efficient.

Despite these large investments in additional phosphorus removal and phosphorus recovery, this would still be insufficient to achieve the 80% phosphorus recycling target for 2050. This demonstrates the challenge of achieving this target. The level of phosphorus removal achieved through these investments would be 89%, which would be adequate to meet the recycling target if all of the phosphorus could be recycled. However, further increasing the level of phosphorus removal achieved at WwTWs may be necessary to achieve the higher recycling targets, especially if not all removed phosphorus is able to be recycled. As shown in Figure 33, the only phosphorus flow from sewage sludge that is not considered as recycled is within the waste ashes. If the amount of phosphorus recovered from the ashes could be increased to 75%, this would provide sufficient phosphorus recovery to meet the 80% phosphorus recycling target by 2050. Any waste ashes which are unsuitable for phosphorus recovery at the time could be stockpiled for future use, a strategy which has been suggested in countries such as Switzerland and Sweden. If the 80% phosphorus recycling target was achieved, this would result in 54.4 kt P being recycled from wastewater each year, which could replace around 75% of the 72 kt P that is currently applied to agriculture within mineral fertilisers. Although this would not completely reduce the reliance on imports, this level of phosphorus recycling from wastewater would make a significant contribution to UK phosphorus security.

From the analysis it is clear that some companies will be able to contribute more to the overall phosphorus recycling targets than others. This phosphorus recycling performance of individual water companies could be included as one of the sustainable indicators presented by Water UK. The PRO scheme is designed to accommodate the different performances by individual water companies by allowing PROCs to be traded between companies, therefore ensuring that phosphorus recovery and recycling activities occur where it is most cost-effective.

The values of the buy-out fees, traded values and surplus fees were set at £1.00, £0.75, and £0.50 respectively. These values resulted in some companies generating significant revenue through the PRO scheme, whilst others would have to pay to comply with the obligation. For example, in the 2025 scenario, it is estimated that Severn Trent would generate £1.5m in the scheme, whilst Scottish Water would be required to pay £0.86m. However, the investments required to meet the phosphorus recycling target, which include investments in additional phosphorus removal and recovery facilities, will cost a substantial amount of money, and it is assumed that it is more cost-effective for some companies, such as Scottish Water, to buy PROCs from other companies and pay the buy-out fee, rather than invest in the technologies required to increase phosphorus recycling. There was insufficient information available to calculate how much it would cost to increase phosphorus recycling within the individual water companies. This information would be required to determine the appropriate value for the PROC's buy-out and surplus fees. As such, the revenues generated and costs to individual water companies should be considered as indicative, rather than as exact values.

Implementing the PRO scheme will cost money. However, as outlined by DECC for the Renewable Energy Roadmap, taking no action is not necessarily the least cost option for the UK economy when considering the potential price rises and value of security of supply (DECC, 2011b). There are many benefits of increased phosphorus recycling from the water industry, and these could outweigh the costs of implementing and running a recycling obligation scheme. However, there was insufficient information available for this research to produce an accurate evaluation of the costs of implementing and running the scheme, or what value increased phosphorus recycling would have to the UK economy. The money required to run this scheme could be generated through the buy-out fees from companies failing to meet their requirements, an industry-wide tax to support the scheme, or, as suggested by Hislop and Hill (2011), through a 'phosphate tax' on mineral fertiliser which raises money to support phosphorus recycling schemes and research, whilst increasing the value of mineral fertilisers and making renewable alternatives more competitive.

The results from this analysis suggest that increased phosphorus recycling within the water industry could be achieved through the use of the PRO scheme developed for this thesis. This would affect individual water companies differently, but overall the increased recycling from wastewater could have a significant impact on UK resource security. Therefore, despite having insufficient information to determine if the investment costs present a significant barrier, it is suggested that the water industry will be required to increase phosphorus recycling in the future.

7.5 Overall Discussion

Phosphorus is now increasingly recognised as a critical resource that should be managed to increase food security for the future. The sustainable supply of phosphorus was highlighted as an issue for global food security within the Roadmap to a Resource Efficient Europe, which established a vision for all resources to be sustainably managed by 2050, and proposed that a Green Paper on Phosphorus should be published (EC, 2011). Furthermore, phosphate rock was recently added to the list of raw materials critical to the EU, and a number of countries, including Sweden, Switzerland, Denmark and Germany, have begun introducing measures and targets for sustainable phosphorus management. It is considered highly likely that similar measures will be introduced in the UK in the near future to address phosphorus security concerns.

The overall aim of this research was to determine if the UK water industry will be required to increase the amount of phosphorus that is recycled from wastewater in the future in order to address national resource security. This research involved: critically analysing current phosphorus management practices and obstacles for resource management of phosphorus in the water industry; quantifying phosphorus flows through the water industry and comparing this to other major phosphorus flows in UK food production system; evaluating the key drivers of global scarcity to determine the relevant timescales for increasing phosphorus security; and finally, developing a phosphorus recycling obligation scheme to determine how specific phosphorus recycling targets could be met, what contributions would be made by the individual water companies, and what impact this would have on UK phosphorus security.

It is clear that the water industry currently manages phosphorus as a pollutant, with most legislation, existing infrastructure and treatment methods designed for environmental protection. However, because of the need to increase phosphorus recycling in the future, and the sheer amount of phosphorus flowing into UK WwTWs each year, phosphorus management in the water industry in the future will become increasingly focussed on recovering phosphorus as a valuable resource to support UK phosphorus security. The analysis of the key drivers for phosphorus scarcity revealed that security of supply could be affected in the short-term; therefore the transition to a more sustainable phosphorus management system is likely to be required soon. Finally, the analysis of a Phosphorus Recycling Obligation (PRO) scheme demonstrated that increasing phosphorus recycling targets, including an 80% phosphorus recycling target by 2050, could be met through a combination of increased phosphorus removal, more efficient recycling of sewage sludge and a significant increases in phosphorus recovery from wastewater and thermal destruction ashes. Each individual water company would play a different role due to the existing infrastructure and geographical position, and the trading mechanism embedded within the PRO scheme was included to ensure that the phosphorus recycling targets are met at the least cost to the industry. Overall, achieving the 80% phosphorus recycling target by 2050 could replace 75% of the current requirement for imported mineral fertilisers, which would significantly increase UK phosphorus security. Increased recycling of other renewable sources of phosphorus, including food waste and animal wastes, and increased agricultural efficiency would be sufficient to completely remove the demand for imported fertilisers within the UK and ensure future food security.

The methods developed for this research include:

- Evaluating current resource management practices, including legislative drivers and existing infrastructure, to identify potential opportunities and obstacles for more sustainable resource management practices.
- Quantifying resource flows within a specific system to reveal the key stakeholders in a resource management strategy.
- Assessing the global drivers of resource scarcity and determining the relevant timeframe for action.
- Developing and testing appropriate strategies to increase recycling of renewable resources.

These methods could be applied to increase the sustainable management of phosphorus and other critical resources in other industries and other countries.

8 CONCLUSIONS

Phosphorus is an essential resource required for food production. The rapid increase in global population, from 1 billion people in 1800 to 7.2 billion in 2012, was made possible by increasing food production and consuming large amounts of resources, including non-renewable resources such as phosphate rock. However, the consumption of non-renewable resources is not sustainable (EC, 2013b). The continued population growth, which is projected to reach 9.6 billion by 2050 and 10.9 billion by 2100 (UN, 2013bUN, 2013b), will consume ever more resources, including phosphate rock as the primary supply of phosphorus, which will put increasing stresses on the food production system.

Increasing the sustainability of the food production system to ensure future food security will require the sustainable management of all resources it depends upon. In particular, this will require a shift away from the current reliance on primary 'fossil' resources, such as phosphate rock, towards increased utilisation of renewable 'secondary' resources, such as phosphorus recycled from food waste, animal manure and sewage sludge. For individual countries, such as the UK, which have no domestic phosphate rock reserves, reducing the reliance on imported resources will also increase security of supply.

Since most of the phosphorus consumed within human food ends up in wastewater, this suggests that the UK water industry will be required to play a key role in future phosphorus management to increase resource security for the UK. However, the water industry has traditionally managed phosphorus as a pollutant, removing it from the final effluent in order to prevent eutrophication and protect the water environment. The aim of this thesis was to determine if the UK water industry will be required to increase the amount of phosphorus that is recycled from wastewater in the future in order to address national resource security. This research was guided by a series of four research questions, and the conclusions to each of these will presented in this section.

8.1 There is the potential to increase the amount of phosphorus recycled from wastewater

The first research question was: How does the UK water industry currently manage phosphorus, and what are the key challenges and opportunities for increasing phosphorus recycling from wastewater? Hypothesis 1 stated that changes to current legislation, existing infrastructure and treatment methods will be required to significantly increase phosphorus recycling from wastewater.

The literature review revealed that the UK water industry currently manages phosphorus as a pollutant, with almost all legislation relating to phosphorus designed to protect the environment. There is now a growing recognition of phosphorus as a future resource issue, with phosphate rock being added to the list of critical raw materials to the EU. Furthermore, a growing number of countries have begun introducing phosphorus management measures, including phosphorus recycling targets from wastewater, although no such legislation currently exists within the UK to increase the amount of phosphorus that is recycled from wastewater.

The knowledge gap identified was the lack of information about the existing wastewater infrastructure and the compatibility with existing technologies designed to remove and recover phosphorus. Therefore, a review of these technologies was undertaken and a significant amount of data was collected from all 12 UK water companies relating to the existing wastewater treatment infrastructure. This data was analysed to determine how compatible the existing infrastructure is with current phosphorus removal and recovery technologies, and what contributions towards increased phosphorus recycling could be made from the individual water companies.

The results revealed that there are currently over 9,200 WwTWs in the UK, but over 80% of the total phosphorus load is received at just 447 larger works (>25,000 p.e.). This is significant for increasing phosphorus recycling since most technologies will be more feasible at the larger treatment works. The results also revealed a considerable difference in the phosphorus loads, population profiles, treatment methods and sludge disposal methods for the individual water companies. This suggests that the approach to increase phosphorus recycling and the potential contribution to UK phosphorus security will be unique to each company. However, due to the size and existing infrastructure, Thames Water and Severn Trent Water are likely to contribute most to phosphorus recycling from the UK water industry.

Phosphorus removal processes are required at 476 works, serving an equivalent population of 20.9 million people. The SFA results revealed that in 2009 around 57% of the phosphorus load to WwTWs was removed. Around 77% of the specific phosphorus removal is undertaken with chemical dosing, in particular through dosing iron salts. This significantly restricts phosphorus recovery processes identified in this analysis. Therefore, increasing the amount of EBPR in the industry would increase the potential for phosphorus recovery, such as struvite. Applied to all WwTWs >130,000 p.e, this could generate approximately 12 kt P/yr, which is equivalent to around 17% of mineral fertiliser phosphorus. The maturation of the technology could also improve this recovery potential.

A combined strategy of recycling sludge to land, and recovering phosphorus from wastewater, sludge and incineration ashes could provide a significant proportion of the phosphorus requirements in UK agriculture. However, the existing infrastructure and legislation are currently designed to remove phosphorus as a pollutant, rather than focusing on recovering and recycling a valuable resource.

The results from this analysis support Hypothesis 1, that changes to current legislation, existing infrastructure and treatment methods will be required to significantly increase phosphorus recycling from wastewater. It is therefore concluded that it would be possible to significantly increase phosphorus recycling from wastewater to help address national resource security, but that additional incentives or regulations will be required.

8.2 The water industry is a key stakeholder in UK phosphorus management

The second research question was: How much phosphorus is found within wastewater and how does this compare to phosphorus flows in other wastes in the UK? Hypothesis 2 stated that there are sufficient quantities of phosphorus within wastewater compared to other waste streams in the UK for the water industry to be considered as a key stakeholder in UK phosphorus management and will therefore be required to play a significant role in increasing phosphorus security.

The literature review revealed that conducting a substance flow analysis, which maps the flows, stocks and losses of a substance such as phosphorus throughout a given system, is an indispensable first step towards managing a resource. However, despite a number of SFAs being developed for other countries, there was not a complete analysis for the UK. Therefore, the relevant data was gathered and analysed, and a SFA for phosphorus in the UK food production and consumption system was produced as part of this research.

The results of the SFA demonstrate that the UK is heavily reliant on imported phosphorus, with net imports totalling around 113.5 kt P in 2009. This confirms that future phosphorus scarcity would have a detrimental impact on the UK food production system. Reducing the requirement for applications of imported mineral fertilisers, estimated at 72 kt P in 2009, was identified as the primary method to increase phosphorus security.

Despite phosphorus flows in the UK being dominated by the agricultural system (for example animal manure is estimated to contain 167 kt P), a significant amount of phosphorus flows through UK WwTWs, estimated at 55 kt P in 2009. Approximately 31.5 kt P is removed within sewage sludge, with 70% of this being recycled to agricultural land, which contains 41% of the total phosphorus load to UK WwTWs. It is estimated that around 23.5 kt P/yr is discharged in the final effluent, which represents the largest loss from the UK system.

The results from this analysis support Hypothesis 2, that there are sufficient quantities of phosphorus within wastewater, sewage sludge and final effluent discharges for the UK water industry to be considered as a key stakeholder in phosphorus management in the UK. It is concluded that increased phosphorus removal and recycling from wastewater could fulfil the joint objectives of increasing the quality of UK waters and increasing national resource security.

8.3 Increased phosphorus recycling from wastewater will be required in the near future to address security of supply concerns

The third research question was: When would an increase in phosphorus recycling from wastewater be required to increase UK phosphorus security? What are the key global drivers of scarcity and timescales associated with each? Hypothesis 3 stated that the risks to security of supply will result in the requirement for the water industry to increase phosphorus recycling from wastewater in the near future.

The literature review revealed that there a number of key drivers for phosphorus scarcity that could impact the UK and drive phosphorus as a resource issue in the UK water industry. An analysis of these drivers revealed that the most commonly used drivers for scarcity, absolute depletion and peak production, are now not expected to occur within the 21st Century as a result of the significant increases in the estimated phosphate rock reserves. Based on USGS 2013 estimates, global phosphate rock reserves would last over 300 years at constant extraction rates, and the supply-sided peak in production is not expected within the next 50 years. These will therefore not be expected to drive phosphorus as a resource issue for the short and medium term, but are threats that will need to be addressed in the future to ensure long term food security.

The short term drivers of global phosphorus scarcity were identified to be created by the intense geopolitical situation surrounding phosphate rock reserves, which could create supply disruptions and price spikes in the short-term. This is driven by the fact that phosphate rock reserves are controlled by just a handful of countries, with Morocco in particular controlling 74% of global reserves. This is considered to be the most pressing concern for UK phosphorus security.

The analysis conducted for this thesis investigated how this geopolitical situation will evolve in the future as a result of many countries depleting their reserves within the 21st Century. The results show that countries currently producing over 70% of the global production, including China and the US, will deplete their reserves this century. This will intensify the geopolitical situation throughout the 21st Century. Furthermore, the increasing demand for phosphate rock will generate an increasing production deficit. Large production increases will have to occur in Morocco to meet this deficit. The results from this analysis suggest that Morocco will produce around 80% of the world's phosphate rock by 2100. The analysis also introduced the concept of 'lag phosphorus', where production continues to increase but is outpaced by demand, therefore creating scarcity and price rises.

To conclude, the intense geopolitical situation may result in supply disruptions and price spikes in the near future, which would affect UK food security. This conclusion supports Hypothesis 3, which states that the risks to security of supply will result in the requirement for the water industry to increase phosphorus recycling from wastewater in the near future.

8.4 A phosphorus recycling obligation could be implemented to increase phosphorus recycling from wastewater

The fourth research question was: What strategy could be developed to encourage the UK water industry to manage phosphorus as a resource, and how would the industry respond to such as strategy? Hypothesis 4 stated that a renewable phosphorus strategy introduced within the water industry would encourage investments in phosphorus removal, recovery, and recycling technologies, which would significantly increase the amount of phosphorus that is recycled from wastewater and make a large contribution towards national resource security.

The literature revealed that there is currently no national-scale phosphorus management strategy for the UK, and hence no legislative drivers for the water industry to increase the amount of phosphorus that is recycled from wastewater. However, the UK manages its energy resources to meet security of supply and environmental objectives, and there are many similarities between developing renewable sources of energy and renewable sources of phosphorus. Hence, the Phosphorus Recycling Obligation (PRO) was developed as part of this research following similar principles established for the Renewables Obligation (RO). The basic principles include companies receiving Phosphorus Recycling Obligation Certificates (PROCs) for each kg of phosphorus that is recycled. Companies must present enough certificates to meet their targets by recycling phosphorus or buying PROCs from other companies. This was designed to encourage the most cost-effective investments throughout the industry. Using a number of assumptions, three scenarios were developed for 2012, 2025 and 2050, in order to determine; if the UK water industry could meet a series of increasing phosphorus recycling targets, including an 80% phosphorus recycling by 2050; how the individual companies would contribute towards meeting these target under the PRO scheme; and what contribution this would have to UK phosphorus security.

The results revealed the importance of increased phosphorus removal to meet future recycling targets. In the 2012 scenario, 58.5% of the phosphorus load to WwTWs was removed. At this rate it would be impossible to meet an 80% phosphorus recycling target, even if all removed phosphorus could be recycled. However, a synergy was identified between increasing phosphorus removal to meet both environmental and recycling objectives. Appropriate phosphorus removal methods will be required to enable both objectives to be achieved, and the introduction of the PRO scheme would ensure phosphorus is also considered from a resource perspective.

The performance of individual companies will vary significantly based on infrastructure and geographical location. However, the PRO scheme will encourage companies to cooperate, trading PROCs to ensure that the industry phosphorus recycling targets are met at the least overall cost.

Despite significant increases in the treatment level at UK WwTWs in the 2050 scenario, including secondary treatment at all WwTWs, 80% phosphorus removal at all WwTWs >10,000 p.e. and 95% phosphorus removal at WwTWs >100,000 p.e., the industry would remain unable to meet the 80% phosphorus recycling target by 2050, recycling 76% of the total phosphorus load. Therefore, even greater investments and increased performance of phosphorus removal, recovery and recycling technologies will be required to meet the 80% target. If this target could be achieved, it would result in over double the amount of phosphorus being recycled compared to today, and could replace around 75% of the phosphorus currently applied to agriculture within imported mineral fertilisers. This would also generate additional revenue for the water industry.

The results from this analysis support Hypothesis 4, which stated that through a specific recycling strategy the amount of phosphorus recycled from wastewater could be significantly increased, which would make a large contribution towards national resource security.

8.5 Final conclusions

This research was guided by the question: Will the UK water industry be required to manage phosphorus as a resource in the future, and could an increase in phosphorus recycling from wastewater contribute to phosphorus security in the UK? Hypothesis 5 stated that the UK water industry will be required to increase the amount of phosphorus that is recycled from wastewater in the near future, and that this shift towards managing phosphorus as a resource could make a significant contribution to UK resource security.

The analyses conducted for this research, which includes the compatibility of existing wastewater infrastructure with phosphorus removal and recovery technologies, the phosphorus flows throughout the UK food production system, the key drivers for global phosphorus scarcity, and the development of the phosphorus recycling obligation scheme, supports Hypothesis 5. It is concluded that increased phosphorus recycling from wastewater will be a requirement in the near future, and that with sufficient investment in phosphorus removal, recovery and recycling operations, the UK water industry could recycle 80% of the influent phosphorus by 2050, which would make a significant contribution to UK phosphorus security.

It is hoped that this research will act as a catalyst for increased phosphorus recycling, in particular from wastewater, in order to slow down the depletion of global phosphate rock reserves, increase phosphorus security, and ensure future food security. Although this research was focussed on the UK and phosphorus recycling in the UK water industry, the methods, results and conclusions are transferable to the sustainable management of phosphorus and other resources in other industries and other countries.

9 RECOMMENDATIONS AND FURTHER RESEARCH REQUIREMENTS

This research has enabled several recommendations to be made for improving phosphorus management in the UK and in other countries. Also, with a subject as broad as phosphorus and resource management, a number of additional research requirements were identified that were beyond the scope of this thesis but should be investigated further. This section details the recommendations and further research requirements for the four key sections of this thesis.

9.1 Recommendations related to the infrastructure of the water industry

1) **Incentivise EBPR –** There are many benefits to EBPR compared to chemical removal. These include reduced consumption of chemicals, reduced sludge production, more available phosphorus in sewage sludge and the ability to recover phosphorus from wastewater and incineration ashes. However, EBPR is typically more expensive than chemical phosphorus removal; therefore additional incentives or regulations may be required to increase the uptake of EBPR.

2) **Capitalise on the phosphorus removal and recovery synergy –** Increased amounts of phosphorus removal will be required to meet WFD targets. This presents the opportunity to couple increased phosphorus removal with increased phosphorus recovery. However, this requires phosphorus removal processes that fulfil both objectives. Additional research would be required to determine if phosphorus removal to meet environmental

objectives will be sufficient to meet phosphorus recycling targets, or if additional phosphorus removal will be required.

3) **Determine the feasibility of continued sewage sludge applications to land -** Sewage sludges are expected to contain increased amounts of phosphorus in the future due to increased phosphorus removal to meet WFD targets. At the same time, the Biosolids Nutrient Management Matrix is applying increasing restrictions on sludge applications to land based on the phosphorus content of the soils. Additional research is required to determine the feasibility of direct recycling of sewage sludge to agricultural land in the future.

4) **Stockpile ashes –** Mono-incineration of sewage sludge produces ashes that contain all of the phosphorus from the sludge. If phosphorus recovery is not feasible, then these ashes should be stockpiled to allow recovery in the future.

5) **Determine the costs and energy requirements for increased phosphorus recycling** – Investments into technological options for increased removal, recovery and recycling of phosphorus will cost money, and could increase energy consumption. Additional research is required to determine how meeting phosphorus recycling targets would increase debt within the water industry and affect its ability to meet carbon reduction commitments.

6) **Produce an accurate assessment of phosphorus flows throughout UK WwTWs –** Accurate measurements would be required to determine how much phosphorus each water company receives and therefore how much it should recycle if a percentage target was introduced. Also, accurate measurements will be required to monitor phosphorus removal and recycling performance over time. If measurements were taken only at works >10,000 p.e., this would cover over 90% of the total population served in the UK. This would provide a good estimate of phosphorus flows through the company's larger works, and similar assumptions could be used to estimate flows through the smaller works.

9.2 Recommendations related to the substance flow analysis

7) **Develop a standardised model for SFAs** – There are now many country-scale SFAs that have been produced, although the presentation styles vary considerably. A standardised model would enable easier comparisons between countries. The standardised model should replace the original models as these are updated over time.

8) **Regularly update the SFA model** - Understanding material flows is important for measuring performance and monitoring progress over time. A body should be established to collect and analyse the relevant data, and publish an annual SFA for phosphorus in the UK.

9) **Develop the sustainable indicators** – A set of indicators of sustainable phosphorus management was developed for this thesis (Section 6.2.7). These indicators could be used to set targets, monitor performance over time and compare performance to other countries. These should be developed further and a body should be established to update these annually, in line with the updated SFA. The phosphorus recycling performance of each water company could also be included within the Sustainability Indicators published by Water UK.

10) **Develop regional-scale SFAs** – Smaller scale SFAs would be more useful to develop regional phosphorus recycling strategies. Additional research could develop the analyses for individual water companies or water catchment areas.

9.3 Recommendations related to global phosphorus security

11) **A detailed inventory of global phosphate rock reserves and resources** – As phosphorus is such an essential resource, an accurate inventory is needed, including a much clearer understanding of size, quality, location and accessibility of global phosphate rock reserves and resources. In particular, since most of the world’s phosphate rock reserves are held by Morocco, an assessment should be undertaken to determine the exact size, quality and availability of these reserves. It should also be made clearer if the reserves are reported as ore or concentrate.

12) **Establish an improved assessment of future phosphorus demand for phosphate rock** – Better estimates of both the future supply and demand for phosphorus from phosphate rock will allow more efficient resource management strategies to be developed. Additional research is needed to develop a model that estimates when a peak or plateau in phosphorus supply and demand will occur.

9.4 Recommendations for establishing a phosphorus management strategy

13) **Long-term phosphorus recycling targets –** phosphorus recycling targets would require the water industry to begin managing phosphorus as a resource. This research recommends an overall target of 80% by 2050, and linear path, reaching 55% by 2025. Additional research is required to determine if the target, timeline and pathway are feasible and cost effective. The targets should be set as legally-binding targets.

14) **Establish the Phosphorus Recycling Obligation scheme –** This research concluded that the PRO scheme, which functions similar to the Renewables Obligation for energy, could be adapted to increase phosphorus recycling in the water industry. Additional research is required, including input from all relevant stakeholders, to develop the PRO scheme further. This would involve additional research to determine the price of the PRO certificates buy-out and surplus fees to ensure that ensures that phosphorus recycling targets are met at least cost.

15) **Investigate banding for PROCs –** Similar to the Renewables Obligation, a banding system could be introduced for the PROCs to encourage the development of a wide range of phosphorus recycling options. Additional research is required to determine the appropriate method of banding.

16) **Establish a market for recovered products** – ensure that recovered products achieve end-of-waste status, becoming recognised fertiliser products that are incentivised to be used in UK agriculture.

17) **Establish a committee on phosphorus security –** Similar to the Committee on Climate Change, the committee would consist of experts who advise the UK government and relevant industries on how to increase phosphorus recycling. This would involve advising what phosphorus recycling targets are reasonable and achievable, and what measures should be implemented to achieve these targets.

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11 APPENDICES

11.1 Appendix A – Paper I

COOPER, J., LOMBARDI, R., BOARDMAN, D. & CARLIELL-MARQUET, C. 2011. The Future Distribution and Production of Global Phosphate Rock Reserves. *Resources, Conservation & Recycling,* 57**,** 78-86.

11.2 Appendix B – Paper II

COOPER, J. & CARLIELL-MARQUET, C. 2013. A Substance Flow Analysis of Phosphorus in the UK Food Production and Consumption System. Resources, Conservation and Recycling, 74, 82-100.