Food Waste Disposers, the Sewers and the Circular Economy

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Declaration

I declare that no portion of the work contained in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning. The work has been my own except where indicated. All quotations have been distinguished by quotation marks and the sources acknowledged.

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Abstract

Domestic food waste is generated through avoidable and unavoidable waste when preparing food in the household. One option of managing domestic food waste is through the use of food waste disposers (FWDs). FWDs are under-sink grinding units used to dispose of domestic food waste via the sewer network. This thesis assesses potential risk and benefit of FWD usage using an evidence based approach. The characteristics of the ground food particles, from a wide range of foods are measured using a series of laboratory studies. Particle size distributions and maximum settling velocity characteristics were measured with settling velocities generally being higher for larger particles, except when particle density and sphericity changes. Due to their high water content, most food types have a particle specific gravity close to unity. The transport behaviour of the particles from food waste disposers is assessed using a hydrodynamic network model of the field site, calibrated and validated using flow survey data, to model particle transport. This allows for the risk of deposition of every particle size of every food type to be assessed in every pipe in the sewer. The transformation of organic food waste in the sewer network is also estimated. For this purpose, COD values of the characterised foods were measured and a rate of transformation of food within wastewater was measured, a modified BOD test was undertaken using potato wherein the rate of biochemical oxygen consumption was measured over a 24h period with and without potato to quantify the degradation of the food waste in-sewer. Using the data collected, the potential for the use of food waste disposers in the circular economy is also examined using the field site as a case study and also the wider implications of the data discussed.

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List of Acronyms

AD	Anaerobic digestion
AHAM	Association of Home Appliance Manufacturers
ASSE	American Society of Sanitary Engineering
BOD	Biochemical oxygen demand
CCTV	Closed-Circuit Television
CIRIA	Construction Industry Research and Information Association,
CIWEM	Chartered Institution of Water and Environmental Management
COD	Chemical oxygen demand
DEFRA	Department for Environment, Food and Rural Affairs
DO	Dissolved oxygen
DWF	Dry weather flow
EMS	Environmental Monitoring Solutions
EU	European Union
FWD	Food waste disposers
GDP	Gross domestic product
LCA	Life cycle assessment
N	Nitrogen
OUR	Oxygen uptake rate
P	Phosphorus
psd	Particle size distribution
RMSE	Root mean square error
RPM	Revolutions per minute
SEE	Standard error of the estimate
TSS	Total suspended solids
WRAP	Waste & Resources Action Programme
WwTP	Waste water treatment plant

1 Introduction

The concept of the circular economy was developed by the Ellen MacArthur Foundation (2020) as an economic system that doesn't create waste and was first used as a term by Kneese's (1988) "The Economics of Natural Resources". Currently most business has been based on a linear economic system whereby a resource is turned into a product and then disposed of as waste. The circular economy principle is to design processes to not create waste, to keep materials in-use and to regenerate the environment (Ellen MacArthur Foundation, 2020). An example of linear economy, with respect to food would be to divert food waste to landfill, where nothing is done to the waste on-site. By contrast, a way of using food waste in the circular economy would be to use food waste as a feedstock for anaerobic digestion (AD). Food waste disposers (FWDs) fit into this process by cutting out transport emissions. This means that instead of food waste being collected by lorries, which mostly are powered by fossil fuels thus emitting carbon in a linear process, the food waste is transported passively using gravity in the sewer which does not require an additional energy input for transport and is using existing infrastructure. Using the sewer network conveniently diverts the food waste to a location which is often have AD: the waste water treatment plant (WWTP). This produces biogas which is used as a power source and also the slurry from the digester can be used as a fertiliser, which in turn can be used to help grow food. How much net carbon is emitted by a process is also accounted for in the circular economy, with AD being an example of a circular way of generating energy and fossil fuel extraction being a linear method of energy generation.

Food waste is both a problem and an opportunity. The waste can be generated at any point; during production, during distribution, in retail and the hospitality industry, and also in domestic households. At every step there can also be avoidable and un-avoidable food waste. An example of avoidable waste is over-purchasing of food and it being wasted due to no one eating it, whereas unavoidable waste would be where certain parts of crops or animals are not edible for consumption. For the purpose of the thesis, domestic food waste is what is being considered, whether it is avoidable or unavoidable.

It has been proposed (KPMG, 2020) that food waste disposers (FWDs) Figure 1 could be a food waste management option that adheres to the circular economy. FWDs are under-sink units which are usually installed in the domestic kitchen whereby they grind up the food waste with running water and the particles produced are washed away by the flow of water into the sewer. The FWD fits into the process chain by removing the food waste from the household and diverting it to waste water treatment plants (WwTPs) where it joins the sludge and can be used to enrich energy production where WwTPs have facilities such as AD. The waste can go into a separate or combined (foul) sewer system, or into a non-mains solution such as a sceptic tank. Whilst the data presented in the thesis could be applied to non-mains wastewater solutions, this has not been examined in the thesis. The focus has been on a separate network so that dry weather flows (DWF) can be used as this will allow for the lowest flows, and therefore the conditions where risk of deposition is highest, to be examined.

Figure 1 A food waste disposer (InSinkerator, 2021)

1.1 Approaches to Food Waste Management

There are a number of distinct approaches to food waste management, the most obvious being to waste less food. Whilst a worthwhile ambition, it is impossible to have zero food waste as the preparation of many foods results in inedible waste such as tough fruit skins (e.g. pineapple skins) and also there is some waste that is edible, such as gizzards and other offal, but that are not consumed for cultural reasons, taste, or due to fashion. This food waste will still need processing.

There are 3 main methods of domestic food waste collection in the UK:

- collection of food in food-only separate collection
- collection of food in food-garden-waste mix collection
- collection of food in the non-recyclable waste

Home composting is utilised in the UK but it is unknown as to what degree. In the (DEFRA, 2021) waste statistics study, it was shown that in 2019 2.0% of total domestic waste was separate food waste collection and 17.0% was organic material suitable for composting which included an unspecified amount of food waste along with other organic compostable wastes. The Waste and Resources Action Programme (WRAP) have also suggested that up to 150 kg per household per year of organic waste can be diverted from disposal using home compost bins (WRAP, 2015).

Kerbside collection is expensive as it involves the vehicle transport, which also emits CO_2, as well as the cost of employing people to move it. The aim of separating the food out from the non-recyclable waste is so that it can be composted or go toward energy generation, however, 40% of UK food waste is diverted to landfill which means that 10.9% of the material going to UK landfill is comprised of food waste (DEFRA, 2011).

Landfill sites are a limited resource in the UK with non-hazardous sites to run out as soon as 2024 according to a 2017 study (Tolvic Consulting, 2017). Landfill can result in pollution and contribute to global warming through the release of greenhouse gases, however gas is often collected (Vaverková, 2019). Food waste can have a high carbon footprint when diverted to landfill; this is because when the food degrades, methane is produced which is then released into the atmosphere if not collected. Compared with molecules of carbon dioxide, a molecule of methane has a much greater greenhouse effect than a molecule of CO_2. Due to the environmental impact potential of food waste, it is important to assess the effect of its disposal.

Food waste processing options can be evaluated using a Life Cycle Assessment (LCA). LCA entails assessing the impact of each option at all stages and determining the least environmentally impacting treatment for food waste. LCAs can give a comprehensive view of the impacts from processes, providing consistent results that are relevant to policy, however it is important to note that they are still a simplified view of reality and work under a number of assumptions (Finnveden, et al., 2007).

Recent LCA studies (Levis, et al., 2010; Levis & Barlaz, 2011) look at food waste treatment and identify that there is a growing need to divert food waste from landfill and that AD and aerobic composting could be potential solutions, but that there is limited research into the emissions associated with the management of organic waste. It suggests as commercial food waste is relatively available, it can be used as a feedstock for AD and aerobic composting. The 2010 study aims to characterise the state-of-the-practice of food waste treatment alternatives in the US and Canada where it highlights 2 implementation issues of the methods; economics and feedstock purity. The 2010 study by Levis et al. assesses the economics using the Intertemporal General Equilibrium Model which factors in policy incentives such as banning food waste to landfill and it suggests that to improve feedstock purity that contaminant standards need to be enforced. In contrast, the 2011 study by Levis & Barlaz asks the question whether biodegradability is a desirable attribute for landfill and used a landfill life cycle model to do so. This includes methane collection and the simulation showed that material with a slow biodegradation rate and lower level of biodegradation enhances the landfill's environmental performance.

It has been shown (Lundie & Peters, 2005) that properly maintained aerobic composting can be the least environmentally damaging food waste management option, however, if improperly maintained, composting can become an anaerobic process and the ensuing methanogenesis renders it one of the lowest performing food waste management options. This is because it is no longer composting in the traditional sense, but is uncontrolled anaerobic digestion. In comparison, the study showed that FWDs are second best in terms of climate change, energy consumption and its acidification potential. However, it had the highest water consumption during operation and also had a high water eutrophication potential due to the additional biomass and nutrients from food waste in ensuing WWTP discharge.

Another LCA research project (Diggelman & Ham, 2003) looks directly at FWDs and compares the impacts of when food is diverted to wastewater and solid waste. This includes two wastewater options, using a FWD to divert to either a rural on-site system or a WWTP, and three solid waste options; landfill, using waste to generate energy and separate collection to compost. The FWD to WWTP option ranked lowest for land requirement, net energy input and greenhouse gas emissions. When looking at costs of having FWDs, 97% of the total system cost is the FWD unit itself with the remaining costs being power and water for processing the food – and all of these costs are borne by the homeowner rather than the council, who pay for the solid waste collection. It is also noted that FWDs have the highest water requirement[1] compared with solid waste and that FWD to a rural on-site system also requires the highest inputs of land, energy, cost and system materials. Although FWDs produce sludge, which needs managing, this can be considered a product as it can be used as farmland fertilizer.

1.2 Case Studies of Food Waste Disposer Use

A prominent long term study is the Surahammar case study (Evans, et al., 2010). This looks at 15 years of sewage works monitoring data to examine the effect of installing food waste disposers in a separate sewer system. Monitoring data was comprised of influent, effluent and biogas data, with the influent data being a 24h composite sample taken every 4 weeks and the effluent being a 24h composite sample taken every 2 weeks. Data collection started in 1995 and FWD installation started in 1997 and by 1998 there was 30% installation and by 2008 this had risen to 50% installation. No difference physically, in terms of rate of corrosion or deterioration to the sewer network was reported and there was no significant change in water use/hydraulic load or in Biochemical Oxygen Demand (BOD) or (Chemical Oxygen Demand) COD. Pest control reported vermin issues with home composting but none with FWD installation. An increase in food waste disposer installation was mirrored by a 46% progressive increase in biogas production by AD at the WWTP which the author presumes is because the additional substrate was composed of particles settled in the primary qualifiers because BOD did not show a significant change.

[1] This does not distinguish the total water use of the FWD: some water going through the unit will be grey water and some will be potable water

A previous study states that FWDs use 0.02kWh/kg of power and 12.4L of water per kg of waste (Lundie & Peters, 2005). Additional overall water use to be attributed to in situ use of FWDs is inconclusive. Some studies reported that more water is used, while some reported less water is used (Nilson, et al., 1990; Karlberg & Norin, 1999) whereas others could not find any per-capita change in water consumption (Jones, 1990). As flow to WWTP does not seem to change significantly with the installation of FWDs (Evans, et al., 2010) it is uncertain what effect FWDs have on water consumption.

A field survey of a medium sized village and a small village in Japan (Yang, et al., 2010) comparing the effect of installing FWDs on the municipal solid waste showed that FWDs on average reduced the generation of solid waste by 31%. This also affected the composition of the remaining collected solid waste garbage, making it drier, which meant that more waste could be compressed into the transport trucks and it had a lower heating value for incineration. The installation of FWDs showed a cost saving benefit in terms of waste management in these areas.

A UK study by Thomas (2011), looks at the effect of FWDs on the wastewater system showed that out of COD, BOD, ammonia, N_{tot}, P_{tot}, Total Suspended Solids (TSS) and rapidly settable solids, the largest impact FWDs made was on the COD, BOD and total suspended solids and that FWDs do create an additional load upon the wastewater system, just that at that time it was unknown how great a load this is (Thomas, 2011).

The UK currently only has about 5% installation of FWDs. There is currently very little information or clear policy regarding the installation of FWDs. The Chartered Institution of Water and Environmental Management (CIWEM) has a generally positive outlook on FWDs and provides a referenced report to support its stance (CIWEM, 2011) whereas Water UK has a negative outlook on FWDs (Water-UK, 2017). Understandably, as the two leading UK water bodies are giving conflicting advice, it means that clear information must be provided to avoid future ambiguity.

One UK study (Iacovidou, et al., 2012) suggests that policy intervention is needed as low FWD uptake would not result in enough savings from avoided waste collection to cover increased costs at the WwTP and that FWDs can only be a viable waste management option with sufficient uptake as otherwise the increase in wastewater cost would not outweigh the savings made. Studies such as Iacovaidou's potentially add to the confusion surrounding FWDs as comments (Evans, 2012) in response to Iacovidou's publication points out that a number of significant pieces of information, which could have led Iacovidou et al., to a more positive conclusion regarding FWD usage, had not been taken into consideration.

1.3 Use of Food Waste to Boost Anaerobic Digestion

Organic waste has significant bio-energy generating potential via AD (Appels, et al., 2011). The addition of food waste to sewage as a co-digestate results in a significant increase in the performance of the AD plant although the uptake of this in the UK is not as common as in other countries (Koch, et al., 2015; Iacovidou, et al., 2012). Specifically, the increase is not only in the yield of methane, but also the accelerated methane production rate (Koch, et al., 2015). Case studies show that there is potential for the majority of the WWTP's energy requirements to be fulfilled when sludge AD is supplemented with food waste (Koch, et al., 2016).

AD has significant biogas potential and is a good candidate for contributing to the sewage related circular economy. However, the financial economics of projects will vary region by region due to a number of variables such as differing efficiencies in the AD process, different nutrient levels in the sewage, the varying cost of accompanying processes and the costs of competing disposal methods. A study by (Kegebein, et al., 2001) suggests that if assuming around 40% efficiency of conversion from biogas to electricity, FWDs have been shown to have the potential to produce 83.2kWh per person per annum. This is a conservative estimate as many biogas units around the world have an electricity conversion efficiency of 45% to 49% (Farooque, et al., 2015), but still a much greater value than the average estimated energy usage of 4.1kWh per annum for a food waste disposer (Keleman & Furlong, 2020).

Nutrients from FWD use can boost AD and enrich sludge. Land degradation is a significant issue across the globe, sludge can be used to bioremediate soils (Thassitou & Arvanitoyannis, 2001) meaning that there is no "waste" in this process.

1.4 Settling Processes in Sewage

Where possible, sewers are designed to be "self-cleansing" using operational flows, though particles may settle when flow velocity is low. Particle depositions however are expected to be re-suspended when velocities increase (Ashley, et al., 2004). In some cases, particles that do not re-suspend with higher velocity flows can cause blockages if they accumulate – large, heavy particles such as gravel are an example.

Sewer sediments are typically deposited during low flows and re-suspended during higher flows. The threshold of motion is when the flow velocity is sufficient to move a sedimented particle. Re-entrainment is when a previously settled particle is picked up by the fluid and carried along. For a specific particle there will be a specific value of shear stress for which the particle will begin to move and if this minimum shear stress is not met then the particle will accumulate.

Other factors affect the accumulation of particles. Cohesion is when particles stick together resulting in a new, bigger particle which often requires a greater shear stress to move which in turn increases the risk of it accumulating. Cohesion is strongest in small particles (micron range) and requires time to occur. Biofilms occur on a surface, such as the surface of the sewer pipe, and are made up of microorganisms plus a sticky extracellular matrix which is excreted by the microorganisms (Wenkai, et al., 2019). The microorganisms feed off available organic material to produce methane and sulphides if respiring anaerobically. This is another reason that water utility companies are averse to the idea of additional organic matter in the sewer as it has the potential to increase biofilms that in turn can create environments that are corrosive and which is damaging to the sewer (Pistor, 1935).

Settling column tests to investigate settling behavior are commonly implemented due to simplicity, low cost and effectiveness. Even using samples with the same characteristics, the settling characteristics observed depend on the technique being used with differences in literature attributed to differing techniques (Aiguier, et al., 1996). Studies have examined the settling processes in sewage (Piro, et al., 2011) and compared methods used, such as the Cergrene, Aston and Camp/Umwelt-und-Fluid-Technik (UFT) methods (Aiguier, et al., 1998).

The Cergrene column has sampling ports along the vertical axis so that when a previously mixed sample separates out into different densities as it settles, samples can be taken from the ports at a known time. The Aston column is a sealed column that can be inverted to look at particles that float or can look at settling in turbulent water. The UFT method uses an Imhoff cone. Settling velocities using UFT are always greater than settling velocities obtained using Aston or Cergrene methods, which the authors attribute to the UFT only observing settleable solids (Aiguier, et al., 1996).

1.5 Current Information on Settling and Characterisation of FWD Processed Food Waste

There is little laboratory research into the settling of particles and existing studies tend to examine food mixes, not individual foods.

A recent detailed analysis (COD, 5-day BOD, P and N content) of a typical US food-waste mix uses a recipe comprised of 33 different types of foods in varying quantitates (Kim, et al., 2015). In this paper the COD of the food waste mix is measured as 1500 ± 470 mg/L for 440g of food suspended in 58L of water (7.59g/L) which means that the COD is 198± 62 mg/g.

A more recent study (Chowdhury, et al., 2016) used the same food mix as Kim, et al. (2015) and examined the flocculent settling of food wastes using a 3.23m Cergrene style column with sampling ports. This did not assess particle settling velocities but instead the rate at which TSS, BOD, COD, N_{tot} and P_{tot} concentrations changed in samples from the column ports. This was to evaluate the change in characteristics of food waste in an environment comparable to primary clarifiers.

It is unknown what the effect of food waste is upon assets such as sewers and WWTPs. A recent study by Thames Water (Thomas, 2011) showed that there was no significant effect on the total rapidly settleable solids in sewage when FWDs were installed, despite the TSS increasing. This suggests that the settling velocity is not high and agrees with Evans et al., 2010 findings in that no settling of sewage particles was observed in the field. The Thames Water study involved collecting food waste from 18 people within Thames Water over 4 consecutive days and the total food waste collected being used on the 5th day. The food was then ground up using a FWD in a lab before being used in the TSS experiment and the COD, BOD, NH_4 and P_{tot} being measured.

However, some studies have indicated that increased volumes of food waste may increase particle settling within sewer networks (Mattsson et al., 2014). No study has as yet rigorously examined the physical and biological characteristics of FWD derived particles, or their transport and transformation within sewers and at treatment plants. These processes are important to understand in order to assess the potential for resource recovery from food waste via the existing sewer and wastewater treatment infrastructure and to identify any risk of blockage.

1.6 Summary

The approaches to food waste management currently commonly implemented show that there is opportunity to investigate alternatives that better fit the circular economy and low carbon emissions concepts. Case studies of FWD use show that there is potential for boosting energy recovery at WwTPs using anaerobic digestion, with there already being existing research on the productivity of co-digesting sewage sludge with food waste. There are a number of techniques for examining settling processes in sewage, but the settling velocity of food waste has not been measured and the rate of food waste degradation has not been measured.

The areas where future research is required lie in the effective quantification of FWD food waste's potential for AD and whether FWD use can reduce the environmental impact of food waste. It is also important to quantify the impact of FWDs on the receiving sewer network and waste water treatment plants. This should make it possible to determine more accurately, in a more informed manner, whether FWD use is an economically and environmentally viable solution to food waste problems.

1.7 Aims & Objectives

Aims

1. Quantify the impacts of the outputs of Food Waste Disposers (FWD) upon the receiving sewer networks and waste water treatment plants.

2. Quantify the biochemical potential for Anaerobic Digestion (AD) at the waste water treatment site from the widespread use of FWDs.

3. Investigate if FWDs can have a significant role in the circular economy and can significantly reduce the environmental impact of food waste in society.

To achieve these specific aims the following objectives have been identified:

Objectives

In order to achieve aim 1, we need to:

- Create a database of particle size distributions and settling velocities of FWD derived particles for foods to facilitate prediction of the particle size profile of different diets and foods. This is addressed in chapter 2.

- Characterise FWD derived particles for common UK foods in each food group so as to assess the transport and deposition potential for FWD derived particles in receiving sewer networks. This is addressed in chapter 2 and 3.

- Create a calibrated hydraulic sewer network model of the field site and validate the model. This is addressed in chapter 3.

- Collect field data to demonstrate that the sewer network model can simulate the hydraulics appropriate for estimating the transport and biodegradation of FWD derived particles. This is addressed in chapter 3.

Building upon the information collected to achieve aim 1, aim 2 also requires that we:

- Determine the rate of biodegradation of FWD derived particles in a sewer network. This is addressed in chapter 4.

- Use the hydraulics from the calibrated hydraulic sewer network model to estimate the transport time which in turn allows for the biodegradation of FWD particles during transport to be estimated using the rate of biodegradation. This is addressed in chapter 5.

- Evaluate the potential for additional biomass' from FWD use to boost AD at the Waste Water Treatment Plant (WWTP). This is addressed in chapter 5.

The final aim, aim 3, uses all of the information gathered for addressing aims 1 and 2, but also requires the following objective:

- Quantify FWDs potential contribution to the circular economy. This is addressed in chapter 5.

1.8 Thesis Structure & Content

The thesis is made up of 6 chapters, with chapter 1 containing an introduction to food waste disposers as a research topic, the aims and objectives of the project and the literature review.

The following chapters 2, 3, 4 and 5, cover the research in themes. The chapters are sequential with the results outlined in chapter 2 feeding into chapter 3 and so forth. Each of these chapters has its own materials and methods section as well as their own results, conclusions and summary for each theme.

Chapter 2 is based upon a paper, published by the author, in the Journal of Water Science and Technology (Legge, et al., 2021).

Legge, A., Nichols, A., Jensen, H., Tait, S., Ashley, R., 2021. The characteristics and in-sewer transport potential of solids derived from domestic food waste disposers. Water science and technology, 83(12), p. 2963–2979

2 Physical characterisation of particles from food waste disposers

Chapter Overview

This chapter aims to assess the transportability of food waste disposer particles within a sewer system. A series of laboratory studies have examined the physical characteristics of solid particles derived from domestic food waste disposers. Particle size distributions and maximum settling velocity characteristics were measured for 18 common food types, and stored in a publicly accessible database. Particle size distributions are shown to fit well with a 2-parameter Gamma distribution. Settling velocity is generally higher for larger particles, except when particle density and sphericity changes. For most food types, particle specific gravity was close to unity. Egg shell particles had a significantly higher specific gravity.

2.1 Introduction

There is considerable debate on the best way to manage the disposal of unavoidable domestic food waste, and there is no clear consensus on the optimum approach (e.g. (Schanes, et al., 2018; Slorach, et al., 2020)). In England, the food waste of more than half of households (54%) is still collected with other solid waste by centralised municipal collection and disposal (WRAP, 2015). In Europe, Member States are required to encourage householders to separate out domestic food waste for home composting or kerbside collection (EU Amending Waste Framework Directive, 2018). However, the effectiveness of this approach has been found to be limited to less than 50% of separable food waste (e.g. (STOWA, 2015)). There are also concerns regarding the overall carbon emissions from kerbside collection. In England kerbside collection is the recommended way forward for all domestic food waste by 2023 (DEFRA, 2020), with resource recovery achieved primarily via municipal authority street collection trucked to dedicated anaerobic digestion (AD) plants. It is recognised that this approach will require considerable investment in vehicles and digestion plants and may also not provide the minimised carbon emissions compared with other waste management options (e.g. (Jenkinson, 2020)).

In a number of regions around the world, domestic food waste is disposed of by discharging it into the wastewater collection system after processing using domestic food waste disposers (mechanical grinders) that break down food into small particles, e.g. in Surahammar, Sweden (Evans, et al., 2010). More than 50% of households in the USA have food waste disposers (American Housing Survey, 2013), in excess of 34% of households in New Zealand and 10% in Canada. In the EU, fewer food waste disposers (FWD) are generally in use, with only 5% of households evidenced in the UK (Iacovidou, et al., 2012). However, there are various initiatives investigating how FWDs can be used to enable householders to separate their food waste at source to enable resource recovery (e.g. (Run4Life, 2020; Bisschops, et al., 2019)). This shift in domestic food 'waste' as part of wastewater inputs to WWTP becoming seen as a potential resource, has come about due to recent concepts such as the circular economy and the need to better manage carbon ((Skambraks, et al., 2017; van Leeuwen, et al., 2018; Velenturf, et al., 2018; Sancho, et al., 2019)).

Although FWDs have been used in domestic kitchens since the 1920s (Atwater, 1947), their effectiveness at grinding domestic food wastes into particles that can be reliably conveyed in sewers has been studied rarely. Although some earlier studies were concerned with the implications for solids conveyance and transformation (e.g. (Jones, 1990)), few have considered the physical characteristics and transport mechanics of FWD particles in sewer networks. Many objections to FWD use are based on anecdotal observations rather than objective, testable data, for example, recent studies such as (Thomsen, et al., 2018), the EU DECISIVE project, assert that ground food introduced to sewers leads to unspecified 'damage' and 'risk' but without providing supporting evidence.

There is only very limited information about how FWD solids move in sewer networks, their deposition likelihood, and their re-entrainment potential. This chapter aims to assess the transportability of food waste disposer particles within a sewer system.

2.1.1 Sewer solids transport & FWD particles

The variety and range of solids entering, depositing and moving in sewers is broad (Ashley, et al., 2004). Where there are sanitary sewers separate from stormwater collection systems, the solids are comprised of domestic, commercial and industrial inputs (e.g. (Alda-Vidal, et al., 2020)). Increased use of FWDs could result in food waste comprising a significant organic load input to sanitary sewers.

Settling and transport of solids by turbulent flows are dependent primarily on particle and flow characteristics. The particle characteristics include particle diameter (*d*), density (ρ_s) and shape. Equation 1 reflects the balance between flow and particle characteristics. In this, w is the particle settling velocity (m/s) and u^* is the boundary shear velocity (m/s), given by Equation 2, for which τ is the boundary shear stress (Pa) and ρ is the fluid density (kg/m^3). The shear velocity reflects the ability of turbulent flows to transport solids, while the particle settling velocity reflects the ability of the solid particle to settle, incorporating particle size, density and shape in a single parameter (Breusers & Raudkivi, 1991).

Equation 1 presents the sedimentation parameter, ξ, which reflects the balance between fluid mobilising forces and the inertia of solid particles

$$\xi = w/u^*$$

Equation 2 Boundary shear velocity

$$u^* = \sqrt{\frac{\tau}{\rho}}$$

According to Breusers & Raudkivi (1991), particles in a turbulent flowing fluid would be expected to settle on to the bed when $\xi > 6$ or to move along the bed as bedload when $6 > \xi > 2$. Below $\xi = 2$, particles will move either in suspension or by intermittent contact with the bed. However, the ranges of this non-dimensional ratio have been determined from observations of granular particles with high sphericity, and whilst indicative of the potential movement of organic particles of low density, investigation is required to confirm these thresholds for low density, irregularly shaped food particles.

Numerous studies have determined that the particle size of wastewater derived organic solids conveyed in sewers are <0.1mm (e.g. (Levine, et al., 1985; Ashley, et al., 2004)) and that the settling velocities of these particles vary widely. For example, Pisano (Pisano, 1996) gives a range from 0.001 – 1 cm/s for all particles conveyed in dry weather flow from samples in the USA and Canada. Michelbach & Whorle (Michelbach & Whorle, 1992) determined settling velocities for particles in dry weather flows for 55 sites in Germany as ranging from 0.01 cm/s – 8.7 cm/s. Given the wide range of organic solids already present, FWD inputs may not substantially change the composition, but the relative impact of FWD inputs have not generally been considered, thus a robust investigation is needed to characterise the properties of FWD derived solids specifically.

The American Society of Sanitary Engineering (ASSE, 2019) provide performance requirements for food waste disposers, primarily that particles no greater than 12.7mm should discharge from the device, and particles greater than 6.4mm should comprise less than 6.25% of the input load. This was specifically for a 454g food mix comprised of steer ribs, carrots, celery and lettuce in equal proportions. The Association of Home Appliance Manufacturers (AHAM, 2009) provided a more detailed protocol for testing, using the same food mix. They suggest using a sieve stack to characterise the spread of particle sizes between 0.425mm, 2.360mm, 6.350mm and 12.700mm sieves, based on the standard Phi scale (Breusers & Raudkivi, 1991).

Previous studies on FWD derived solids have used sieve testing to determine particle size, but without a consistent sieve stack, consistent procedure, or consistent food mix. Therefore, comparisons of results for the characteristics of FWD derived solids is problematic. Kegebein et al. (2001) used six sieve sizes and considered sixteen foods (some mixed), and also the settling behaviour of food mixes. The majority of particles were smaller than 2mm and the settling velocity was up to around 0.06 m/s. Galil & Shpiner (2001) used five sieve sizes to examine unspecified food mixes from FWDs with different grind speeds to determine that the majority of particles were <2.9mm in size and that 'scouring' velocities were from 0.5m/s for the lightest particles up to 0.84m/s for some particles of egg shell and bone (although it was noted that this high scour velocity could correspond to only a “very small part of the ground material”). These results were based on an adjusted Camp’s formula (Equation 3) using particle relative densities (by comparing with sucrose solutions of known density), of 1.0 to 1.1 for “ordinary basket” particles (no egg shell or bone) and up to 2.3 for bones and egg shell.

Equation 3 Camps formula. Vc is the scouring velocity in m/s; Sp relative particle density; d particle diameter (m); n Manning’s roughness coefficient; R hydraulic radius (m); B is a non-dimensional coefficient related to particle type (0.04 for initiation of movement of granular particles; 0.06 for “sticky” particles; 0.8 for fine cleaning of sewer)

$$Vc = \frac{1.486}{n} R^{\frac{1}{6}} \sqrt{B\ (Sp - 1)d}$$

B is a non-dimensional experimentally derived empirical coefficient which is related to particle type. It reflects physical processes in a coefficient with lower values indicating sticky particles and higher values indicating non-sticky particles. *B* = 0.06 was used by Galil & Shpiner (2001) in the calculations for the “ordinary basket” particles and even with a range of sewer sizes (up to 800mm) and relative flow depths (from 0.25-0.75), the particles were found to be conveyed at velocities as low as 0.5m/s. These findings indicated that FWD solids will mainly be transported without deposition in the sewers considered in the Galil & Shpiner (2001) study. However, the denser particles, including ground egg shells (2241 kg/m^3) were found likely to deposit temporarily during low flow periods, as found by Mattsson et al. (2014).

Channon et al. (2013) used food mixes and five types of FWD, with only two sieve sizes, to show that the majority of the emitted particles were <4mm in size, although there were variations in the results depending upon the type of FWD used. Drinkwater et al. (2015) used only three sieve sizes to determine that the majority of FWD particles were <5.6mm in size. In this study, it was claimed that FWD solids could lead to blockage problems if input to sewer networks, while the other studies mentioned above suggested the heaviest FWD particles would only temporarily deposit before being scoured during the peaks of dry weather flows.

Critically, the literature described above provides little means to predict deposition risk of FWD derived particles in sewer systems. This chapter reports on work designed to determine the physical nature of FWD derived solids, using a repeatable and rigorous set of tests, to address the question as to when, where and how FWD derived solids can be conveyed or deposited in sewer networks.

A key knowledge gap in the assessment of the use of FWDs is the risk associated with using conventional wastewater collection systems (sewers) as the transport conduit for the ground food waste solids. There have been a number of individual observations in the field that FWD particles can deposit in sewer systems and possibly create problems as outlined above (e.g. (Mattsson, et al., 2014; Drinkwater, et al., 2015)). In the study reported here the intention was to establish an experimental protocol to collect high quality (repeatable) particle characterisation data in order to determine when there may be an in-sewer deposition risk from FWD particles.

Laboratory measurements are described which aimed to determine the physical size and fall velocity distributions of FWD derived particles for a wide range of food types. The food types selected were the more common components of food mixes currently found in the UK and USA, so that the impact of individual food type characteristics on representative particle mixtures may be examined.

2.2 Method

2.2.1 Food types and food mixes

This thesis considers the term “food type” to represent an individual food (e.g. carrot) while “food group” refers to the broader category (e.g. vegetables). The chapter aims to characterise a range of common food types (e.g. potato, onion and carrot) spanning several food groups, e.g. vegetables and fruit. FWD particles from these different food types were expected to exhibit a variable range of physical characteristics.

Published data for food waste generation in UK households (WRAP, 2009), and US households (Kim, et al., 2015) was used to select a range of foods for study.

Table 1 shows the typical overall composition[2] of food waste (referred to as a “food waste mix”) in the UK (WRAP, 2009) and in the US (Kim, et al., 2015). This shows that: (i) many of the same food types appear in both mixes; (ii) there are substantial differences in the proportions of individual foods; (iii) different food groupings are used in the UK and USA.

Table 1 UK and US food waste mixes, groups and types (WRAP, 2009; Kim et al., 2015). Percentages are of unprocessed (not dried) food waste by mass. Percentages of food groups (e.g. vegetables) indicate the proportion of each food mix (UK or US), while percentages of food items (e.g. potato) indicate their proportion within each food group. The percentage characterised indicates the proportion of each food group characterised, and the scale factor is thus used to scale the results from this study to represent the whole group.

UK food waste mix (WRAP, 2009)			
Vegetables (38%)		Bakery (16%)	
Potato*	40.1%	Bread*	82.5%
Mixed	13.0%	Speciality	10.1%
Onion	6.8%	Morning bread	1.9%
Carrot*	6.2%	Other	5.5%
Cabbage*	4.4%	*Characterised	82.5%
Lettuce	3.5%	Meat/Fish (12%)	
Tomato	3.3%	Poultry*	48.8%
Roots	2.5%	Pork	19.5%
Cucumber	2.3%	Fish*	7.0%
Corn	2.2%	Lamb	5.2%
Broccoli*	2.1%	Other*	19.5%
Cauliflower	2.1%	Characterised*	75.5%
Salad	1.9%	Processed Vegetables	
Bean	1.5%	Potato*	36.3%
Pepper	1.2%	Slaw/humus	14.7%
Leek	1.0%	Other	49.0%
Mushroom	0.8%	*Characterised	36.3%
Spring onion	0.4%	Staples (4%)	
Other	4.5%	Cereal*	36.8%
*Characterised	52.9%	Rice*	31.4%
Fruit (22%)		Pasta*	20.6%
Banana	28.5%	Flour	0.0%
Apple*	23.9%	Other	11.3%
Orange*	12.0%	*Characterised	88.7%
Melon	9.2%	Dairy/Eggs (3%)	
Stone fruit	6.2%	Egg shell*	38.6%
Other citrus	4.1%	Cheese*	27.1%
Berroes	4.1%	Egg	17.1%
Other	12.0%	Other	17.1%
*Characterised	35.9%	*Characterised	65.7%

US food waste mix (Kim et al., 2015)			
Fruit (37%)		Grains (21%	
Grapefruit	31.3%	Spaghetti	22.2%
Banana peel	15.6%	Mac & cheese	16.7%
Watermelon	15.6%	Rice, cooked*	16.7%
Pineapple*	12.5%	Corn flakes*	11.1%
Apple*	9.4%	Cheerios	11.1%
Orange peel*	9.4%	Bread, white*	11.1%
Cantaloupe	6.3%	Sugar	11.1%
*Characterised	31.3%	*Characterised	38.9%
Vegetables (28%)		Meat (9%)	
Cabbage*	24.5%	Beef*	40.0%
Potato*	22.4%	Pork	26.7%
Lettuce	16.3%	Raw chicken skin	20.0%
Broccili*	12.2%	Hot dog	13.3%
Carrot*	8.2%	*Characterised	40.0%
Celery*	8.2%	Dairy	
Cucumber	4.1%	Cheese*	40.0%
Pepper	4.1%	Cottage cheese	40.0%
*Characterised	75.5%	Butter	20.0%
		*Characterised	40.0%

[2] Note: Table 1 does not sum to 100% due to the effect of rounding

Eighteen different solid food types have been characterised, shown to be significant in UK and US diets in

Table 1 (indicated by *). These food types span all major food groups. The food types examined are shown in Table 2, and were selected to provide a range of common foods found in both UK (WRAP, 2009) and US (Kim, et al., 2015) food mixes and that were expected to demonstrate a range of different properties when processed by FWD. Foods were raw unless otherwise stated in Table 2. Beef and chicken were purchased in cooked form, while pasta and rice were cooked according to manufacturer instructions.

Table 2 Food types used

Food type	UK food group	US food group	Details	Brand
Apple	Fruit	Fruit	Pink lady	Tesco
Beef	Meat/fish	Meat	Cooked slices	Tesco finest
Broccoli stem	Vegetables	Vegetables	Pre-packed	Tesco
Cabbage	Vegetables	Vegetables	Sweetheart	Tesco
Carrot	Vegetables	Vegetables	Batons	Tesco
Celery	Vegetables	Vegetables	-	Tesco
Cheese	Dairy/eggs	Dairy	Mature Cheddar	Cathedral City
Chicken carcass	Meat/fish	-	Pre-cooked, meat removed	Tesco
Cornflakes	Staples	Grains	-	Kellogg’s
Egg shell	Dairy/eggs	-	Chicken eggs	Various
Orange peel	Fruit	Fruit	Cambria Naval	Tesco
Pasta	Staples	-	Fresh penne (cooked)	Tesco
Pineapple	Fruit	Fruit	Costa-Rica	Co-op
Potato	Vegetables	Vegetables	Maris Piper	Tesco
Rice	Staples	Grains	Basmati pouch (cooked)	Tilda
Sunflower seeds	-	-	-	Tesco
White bread	Bakery	Grains	Toastie	Warburton's
Whole mackerel	Meat/fish	-	Gutted	Independent fishmonger

2.2.2 Experimental overview

The experimental work was undertaken in several stages – (i) initial food processing; (ii) particle size characterisation; (iii) measurement of particle settling velocity; (iv) examination of re-entrainment of particles most likely to settle.

The primary equipment is shown in Figure 2, comprised of a FWD linked to a sealed unit to collect all the food particles, a water supply, a set of calibrated, graduated sieves, and a 290mm diameter 1293mm length settling column.

All aspects of the particle measurement and characterisation took place on the same working day for each sample of ground food waste to ensure that the particles did not degrade between the different measurements. A detailed measurement protocol was followed according to the laboratory procedure described in detail by Nichols et al. (2020), and is summarised here. The entire process (from initial food processing to particle size and fall velocity measurement) was repeated three times for each food type to quantify experimental variability and the data was then averaged.

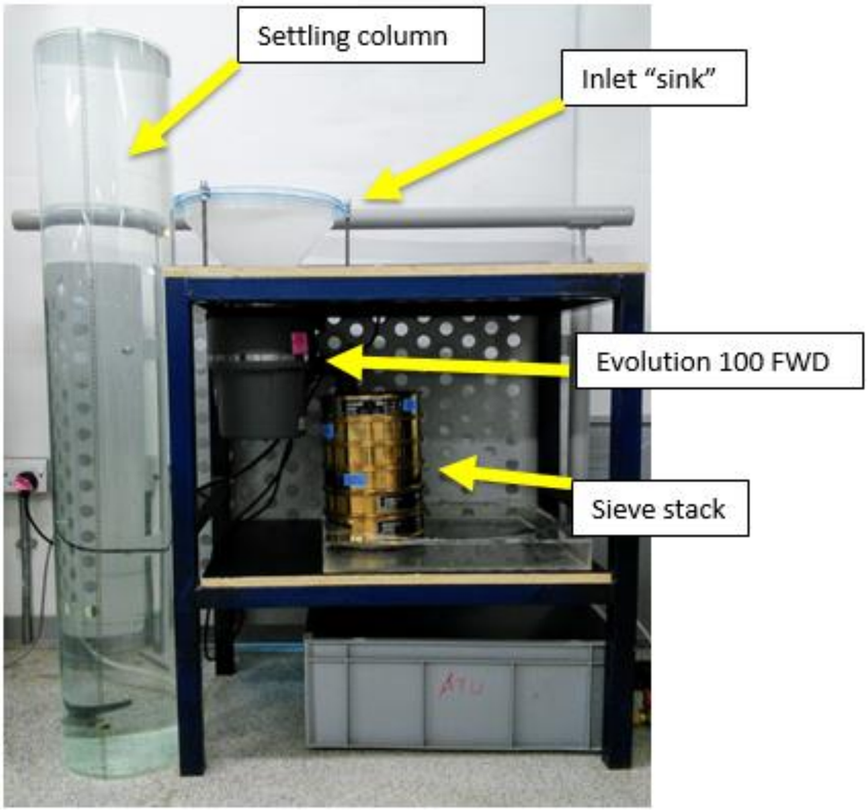

Figure 2 Laboratory equipment - for the testing of an Evolution 100 Food Waste Disposer

2.2.2 Initial Food processing

Food samples were obtained from a standard commercial source (Table 2) and stored according to the supplier instructions. Food was prepared by cutting into pieces small enough to fit into the FWD unit (3-4 cm approximately in each dimension). Foods were prepared in samples of around 500g (+/- 5% as per AHAM, 2009), with the exact mass of each sample being recorded. Egg shells were mostly in a halved state (not crushed), and were rinsed before being introduced to the FWD.

The FWD used was an Insinkerator Evolution 100-1B (serial number 16093104329). The same FWD unit was used for all food types. The water supply to the FWD was turned on and supplied a constant flow of 0.17 l/s. Water was always below 27°C (AHAM, 2009). The entire 500g (+/- 5%) food sample was added into the FWD. The water supply was maintained until no visible particles could be seen exiting the disposer. This period lasted around 50-60 seconds in all tests for this constant flow rate. Any variation in water used between tests did not appear to link to food type.

The mixture of water and food particles exiting the disposer was collected in a clean and dry laboratory container.

2.2.3 Measurement of Particle Size Distribution

The purpose of this measurement was to determine the mass proportion of the original food sample ground into certain sieve size fractions. A stack of sieves was used according to BS ISO 3310-1:2016 and BS ISO 3310-2:2013 to characterise the particle size distribution. This uses the phi (φ) scale which is a logarithmic scale that enables more nuanced inspection of trends for the finer particles. It is a standard scale for measurement and interpretation of sewer solids. The Phi unit is calculated from the sieve opening size in mm in *Equation 4*.

Equation 4 Conversion of phi to mm

$$Phi = log_2(d)$$

So, a small phi value indicates a large sieve size (e.g. -3phi = 8mm) and a large phi value indicates a small sieve size (e.g. 4phi = 0.0625mm). The sieve sizes used ranged from -3φ to +4φ and were arranged in 0.5φ increments (where sieve size in mm is given by $2^{-\varphi}$, and thus ranged from 0.06mm to 8.00mm). This provides a broader range and higher resolution than that suggested in the AHAM (2009) protocol. The water and particle mixture collected from the FWD was stirred to fully suspend the particles and tipped smoothly into the top of the sieve stack, ensuring all of the particles were emptied from the container, undamaged by rinsing.

Beginning with the top sieve, a small water flow was used to gently wash particles through into the next sieve if they were smaller than the sieve size, without visibly damaging the particles. This was repeated sieve by sieve, down the stack, spending at least 5 minutes on each sieve to ensure all particles smaller than the sieve size were carefully washed through. Once the particles had been separated on the sieves, the sieves had the excess water removed by firmly tapping them one-by-one repeatedly above a sink until no more excess water was being released. Each sieve (including the particles) was then weighed using a calibrated electronic balance, with a resolution of 0.1g. The particle sizes were not cross-checked by independent measurement.

Particles were collected from the sieves to be used in the particle settling velocity measurement, and the sieves were thoroughly washed. The wet sieves were then tapped again to remove excess water, and were weighed (without particles). The wet sieve mass was subtracted from the wet sieve mass with particles to give the mass of wet particles collected in each sieve. The proportion in each sieve was calculated as the ratio of the wet food mass in each sieve to the total wet food mass across all sieves multiplied by 100%, following the AHAM (2009) protocol. This process was repeated 3 times for each sample for each food type and averaged, again according to AHAM (2009).

It is worth noting that the sieving process is not infallible. The process makes the assumption that all particles are spherical and it has been established that the particles are not. The particles at the larger end of the spectrum can be stringy or oblong in shape and tend to rest in the larger sieve sizes. This is because the rinsing of particles through each sieve is gentle, so the particles don't tend to be upended in a way that the particle is orientated with its smallest dimension perpendicular to the sieve-mesh. The same principle applies for deformable particles, as the rinsing is not pressurised these particles are not forced through the sieve-mesh and will only pass through if the particle is smaller than the size of the hole. In addition, as the food is weighed when dry (before entering the FWD) the water that remains adhered to the particles during sieving may add some weight and for foods that have a high water content, some water content may be lost via sieving as water will not be captured by the sieves and the same goes for any particles smaller than the smallest sieve size. Despite these discrepancies, the sum of the size fractions should add up to approximately the same mass as put into the food waste disposer.

2.2.4 Settling velocity

The maximum settling velocity of the food particles within each sieve size fraction for each food type was measured. This provided the information needed to determine the likelihood of those particles settling within a sewer flow (Equation 1). 2g samples of food particles were taken from each sieve, mixed carefully to ensure uniformity. The 2g sample was mixed with 15ml of water to form a suspension before being carefully tipped into the centre of the 295mm diameter settling column's water surface, without giving the food particles any initial vertical velocity. This sample-suspension was determined through trial and error; the water used to prevent the sample sticking to the beaker and the sample size so that it is big enough that it is visible in the column, but not so big that the particles interacted with each other. It is worth noting that certain samples, such as celery, are translucent and the particles become difficult to see when looking at the smallest particle size fractions.

Settling time was recorded using a stopwatch at regular intervals throughout the 1293m long column to determine the point at which a stable terminal velocity was reached. For all foods, terminal velocity occurred by 385mm below the water level. The time taken for the fastest falling particle to travel a distance of 710mm below this height was recorded. The fastest falling particle, identified by being at the leading edge of the particle plume, within each size fraction was tracked by eye as this represents the greatest settling velocity for that fraction. The settling velocity of each size fraction for each of the food types was measured 3 times to assess variability and then averaged. The maximum settling velocity reported was therefore an average of three separate measurements. This data is then used to create a profile of the velocity against size of particle.

2.2.5 Particle Entrainment

As both the particle size distribution (psd) and the fall velocity distribution by mass fraction had been obtained from all the food groups it was possible to estimate the solid density of particles of a particular size fraction. This was done so as to estimate the boundary shear stress at the threshold of motion. The size fraction through which 95% of the mass is finer (d_{95}) was selected as the practical maximum particle size for the ground food waste of each food group. Once this was calculated by interpolation of the psd data, the fall velocity for that particle size (V_{95}) was also estimated by interpolation of the fall velocity data. The Reynolds Number (Equation 5) associated with the size faction d_{95} was calculated and this was used to estimate the drag coefficient C_D using Equation 6 (Barati, 2014). Once this had been obtained then the solid density of the ground food waste (ρ_s) for the d_{95} size fraction could be obtained using Equation 7. Both Equation 6 and Equation 7 assume that the particles are spherical in shape.

Equation 5 Reynolds number. μ is the dynamic viscosity of the fluid (kg/(m.s)); ρ is fluid density (kg/m³); V fluid velocity (m/s); d is pipe diameter (m)

$$Re = \rho V_{95} d_{95} / \mu$$

Equation 6 Drag coefficient

$$C_D = \frac{24}{Re} + \frac{3}{\sqrt{Re}} + 0.34$$

Equation 7 Force balance equation for a sphere falling in a fluid at terminal velocity

$$\rho_s = \left[\frac{3V_{95}^2 C_D \rho}{4gd_{95}}\right] + \rho$$

Egg shell was identified by previous field studies (Mattsson, et al., 2014) as a food type more likely to settle within sewers. Given the higher particle density and the irregular shape of egg shell particles, additional experiments were carried out to better ascertain the shear stress required to mobilise deposited egg shell particles as a function of their size, density and the ambient flow conditions. The results were then used to determine the equivalent spherical particles with similar behaviour, as used in conventional threshold of particle motion relationships.

An erosion meter based on the design of Liem et al. (1997) was used to determine the particle transport potential of egg shell. The test involves measuring the threshold of entrainment for different fractions of particles in an erosion meter which relies on a propeller to create turbulence. From this it can be determined the amount of shear stress required to move the particles.

First, a shear stress calibration was performed using sands of different sizes, and the frequency of rotation at the threshold of motion for each size was determined, so that a bed shear could be estimated with a fixed value of Shields' number, as given in Equation 8 where Θ is the Shields' number, $\tau_c$the critical shear stress (Pa), ρ_s is the particle density (Kg/m^3), ρ is the fluid density (Kg/m^3), g is the acceleration due to gravity (9.81 m/s^2), and d is the particle diameter (m).

Equation 8 Shields Equation

$$\Theta = \frac{\tau_c}{(\rho_s - \rho)gd}$$

This follows the methodology described in Seco et al., (2014). This procedure enabled a linear fit to characterise the relationship between the angular velocity of the propeller and bed shear stress, given in Equation 9, where ω is the angular velocity of the propeller in revolutions per minute.

Equation 9 Relationship between the angular velocity of the propeller (m/s) and bed shear stress (Pa)

$$\tau = 0.075\omega - 1.055$$

This expression fitted the data with a coefficient of determination of 0.995. The expression was used to determine the applied bed shear stress at the threshold of motion for egg shell particles based on the measured angular propeller velocity.

Egg shells were processed using the FWD according to the method described in section 3.1. The shell particles were sieved into 9 size fractions ranging from 0.16mm to 4.5mm. For each size fraction, a sample was collected and placed in the base of the erosion meter such that an even bed was formed with the surface of the egg shell deposit 30mm below the propeller (the same distance as used for the sand calibration). The angular velocity of the propeller was increased from zero in increments of 1 revolution per minute (RPM) until sustained motion of particles was observed (taken as several particles in motion at all times). Equation 9 was used to convert this angular velocity into a shear stress for the egg shell particles at the threshold of motion. Measurements using the egg shells were repeated twice for each size fraction to quantify a representative average and assess experimental variability.

2.3 Results & Discussion

2.3.1 Particle Size Distribution

The bin centre on the horizontal axis is the centre of the size range captured by each sieve, in units of phi. Figure 3 shows that the particle size distributions were generally unimodal and demonstrated a wide range of sizes. For the 18 food types measured, the modal particle size occurred in the range of 0.59mm to 4.76mm. The mean particle size of each distribution ranged from 0.58mm to 2.70mm.

Figure 3 shows the particle size distributions by mass on a phi scale for all 18 food types tested. Figure 4 presents the cumulative mass distribution. In both figures error bars represent standard deviation observed for 3 repeated measurements.
The narrowest size distribution was for rice, which showed a much more prominent mode (most common size fraction), as the rice particles were already close to this modal size when entering the FWD. The width of each distribution is quantified via the standard deviation, as shown in Figure 3 and Table 3.

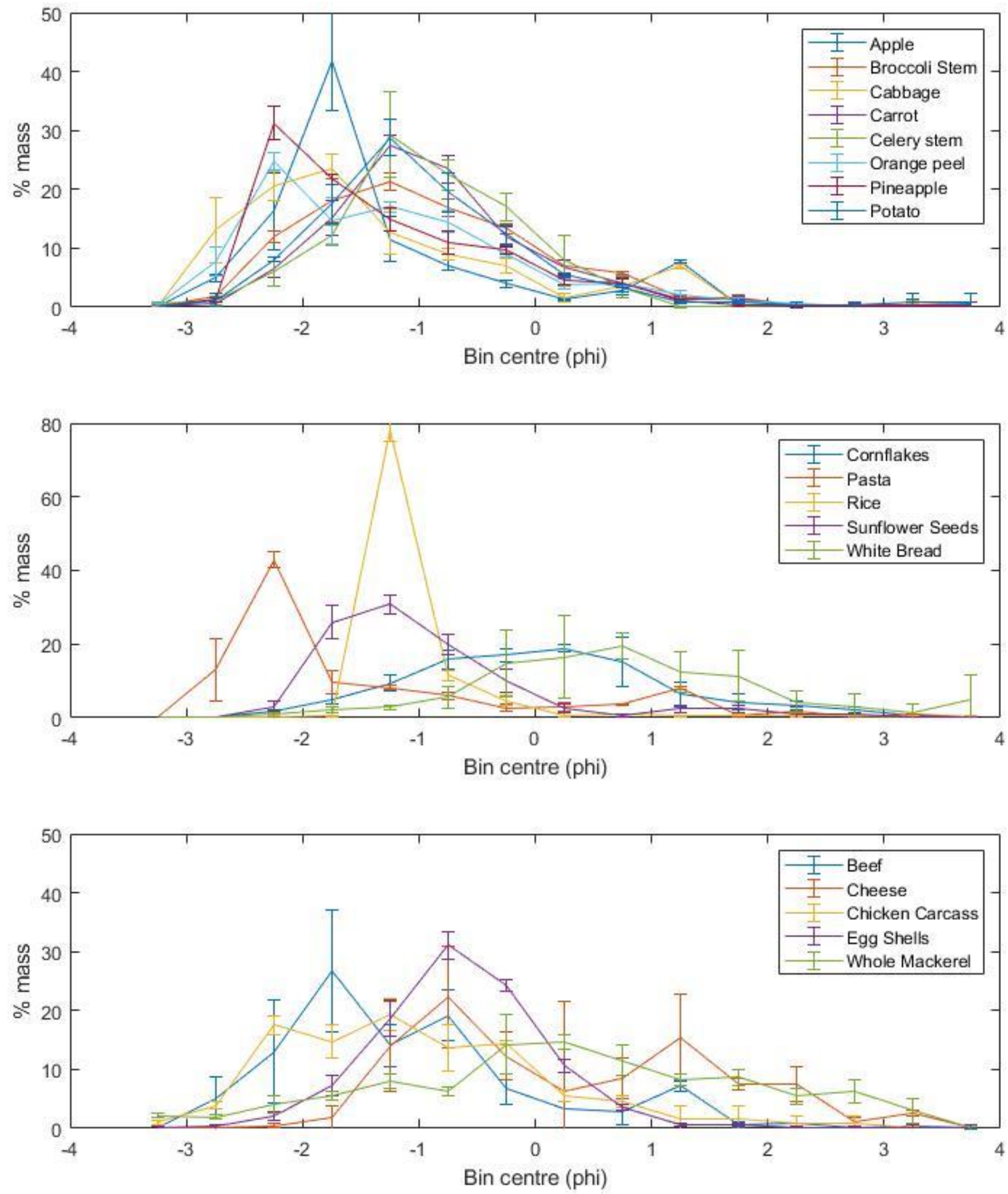

Figure 3 Particle size distribution for 18 food types: (top) vegetables & fruit; (middle) bakery & staples; (3) meat/fish & dairy/eggs. Error bars represent standard deviation from repeated measurements.Note: Phi is a logarithmic scale; a small phi value indicates a large sieve size (e.g. -3phi = 8mm) and a large phi value indicates a small sieve size (e.g. 4phi = 0.0625mm)

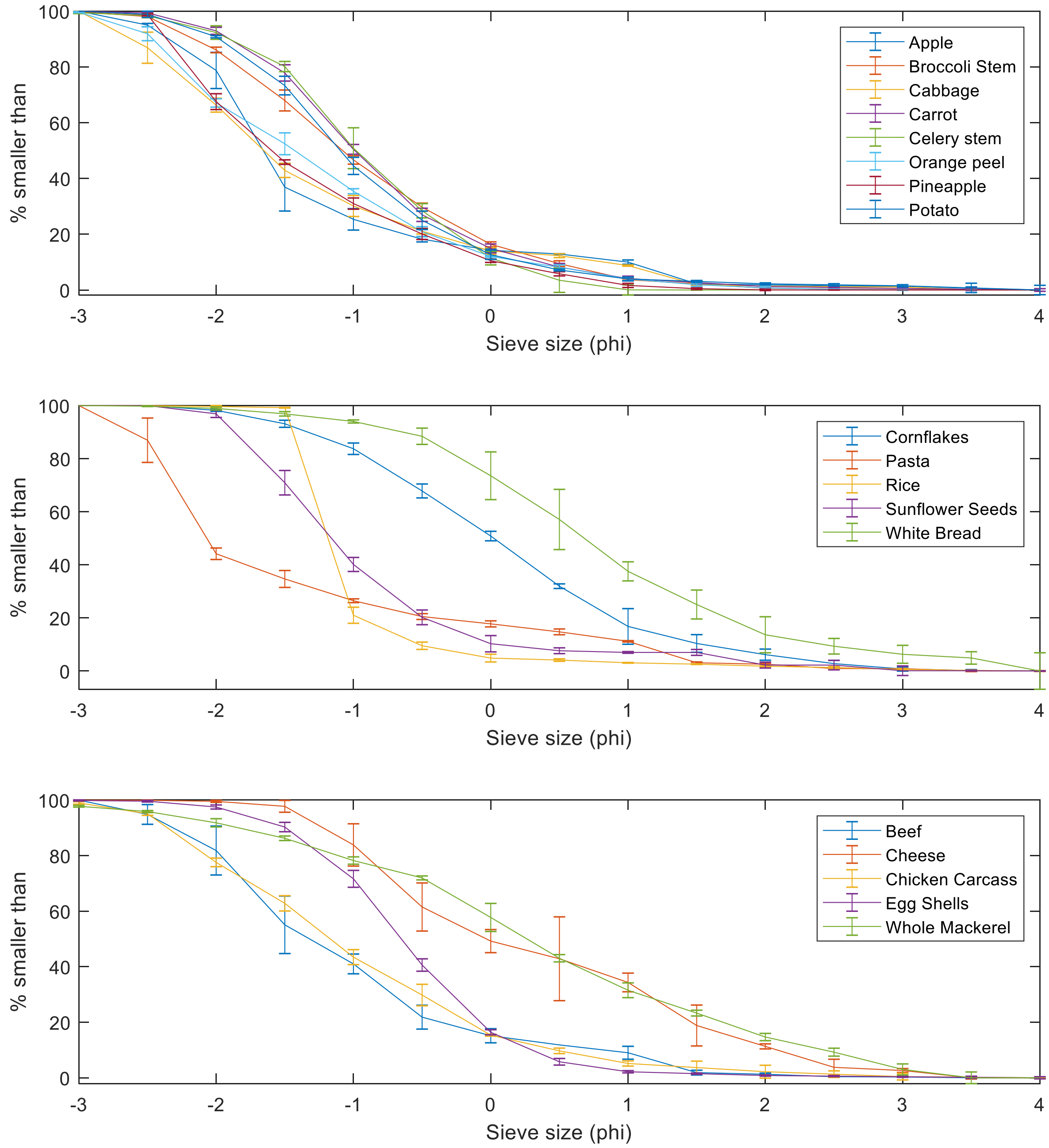

Figure 4 Cumulative size distribution for 18 food types: (top) vegetables & fruit; (middle) bakery & staples; (3) meat/fish & dairy/eggs. Error bars represent standard deviation of repeated measurements. Note: Phi is a logarithmic scale; a small phi value indicates a large sieve size (e.g. -3phi = 8mm) and a large phi value indicates a small sieve size (e.g. 4phi = 0.0625mm)

Table 3 Mean particle size and standard deviation for the 18 characterised food types, ordered by mean particle size

Food type	Mean particle size (Phi)	Standard deviation (Phi)	Mode (Phi)	Mean particle size (mm)	Standard deviation (mm)	Mode (mm)
Pasta	-1.43	1.38	-2.25	2.7	0.39	4.76
Pineapple	-1.34	0.95	-2.25	2.53	0.52	4.76
Cabbage	-1.31	1.25	-1.75	2.48	0.42	3.36
Orange peel	-1.28	1.09	-2.25	2.42	0.47	4.76
Apple	-1.26	1.22	-1.75	2.39	0.43	3.36
Beef	-1.08	1.13	-1.75	2.11	0.46	3.36
Chicken carcass	-1.02	1.16	-1.25	2.03	0.45	2.38
Rice	-1.01	0.7	-1.25	2.01	0.62	2.38
Broccoli stem	-0.94	1.01	-1.25	1.92	0.5	2.38
Sunflower seeds	-0.94	0.96	-1.25	1.92	0.51	2.38
Cheese	-0.93	0.76	-1.25	1.9	0.59	2.38
Potato	-0.92	1.02	-1.25	1.89	0.49	2.38
Carrot	-0.85	0.94	-1.25	1.8	0.52	2.38
Egg shell	-0.61	0.77	-0.75	1.53	0.59	1.68
Cornflakes	0.06	1.11	0.25	0.96	0.46	0.84
Whole mackerel	0.27	1.54	0.25	0.83	0.34	0.84
Celery	0.28	1.27	-0.75	0.82	0.41	1.68
White bread	0.78	1.25	0.75	0.58	0.42	0.59

A number of analytical distribution types are known to be used to characterise particle size distributions in soils and other granular materials. This enables empirically derived distributions to be approximated by a simple analytical expression with a small number of parameters. A common distribution function for particle size distributions is the Gamma distribution (Equation 10):

Equation 10 Gamma distribution

$$f(x) = \frac{(x/b)^{a-1}\exp(-x/b)}{b\Gamma(a)}$$

Where x is the positive particle size, a is the shape parameter (producing a unimodal skewed distribution for $a > 1$, with less skew as a increases), b is the scale factor (which has the effect of stretching or compressing the range of the distribution), and Γ is the Gamma function.

For each food type, a Gamma distribution was fitted to the particle size distribution data using a least-mean-squares optimisation method. The optimised values of a and b are presented in Table 4, along with the root-mean-square error in units of percentage points.

Table 4 Gamma distribution parameters and root-mean-square error of optimised Gamma distributions, ordered by best fit

Food type	**a**	**b**	**RMS error (% points)**
Rice	39.21	0.06	1.93
Egg shell	6.13	0.33	0.93
Apple	10.14	0.39	4.45
White bread	2.92	0.39	1.64
Sunflower seeds	6.77	0.44	1.90
Pasta	12.20	0.44	5.47
Celery	5.07	0.52	1.51
Carrot	4.90	0.57	1.11
Cornflakes	2.99	0.60	1.21
Potato	4.86	0.62	1.16
Pineapple	4.69	0.98	4.11
Broccoli stem	3.46	1.01	0.83
Cheese	2.28	1.01	3.94
Beef	3.76	1.08	3.10
Whole mackerel	1.87	1.21	1.96
Cabbage	3.87	1.33	2.61
Chicken carcass	3.00	1.39	1.94
Orange peel	3.27	1.49	2.76

The a parameter is always above 1, meaning a “humped” distribution shape, and varying generally between 2 and 13 as distributions are more or less skewed. Rice is a clear outlier with $a = 39.21$ as the distribution is a very clear and symmetrical peak (see Figure 3). The b parameter generally varies between 0.3 and 1.5 as the distributions are broader or narrower, again with rice as an outlier at $b = 0.06$ as the distribution is very narrow. There appears to be no clear pattern of certain food groups exhibiting certain distribution parameters.

It can be seen that the majority of foods have a root-mean-square error below 3 percentage points, indicating that the Gamma distribution fits very well. The worst fits were obtained for pasta, apple and pineapple. This is likely due to the partially irregular and/or bimodal nature of their size distributions (see Figure 3). The psd and fitted Gamma curves for these three foods are shown in Figure 5 along with the best case fit (broccoli stem) for reference. The highest error of 5.47 percentage points for pasta is still a reasonably good fit and characterises the general shape of the distribution.

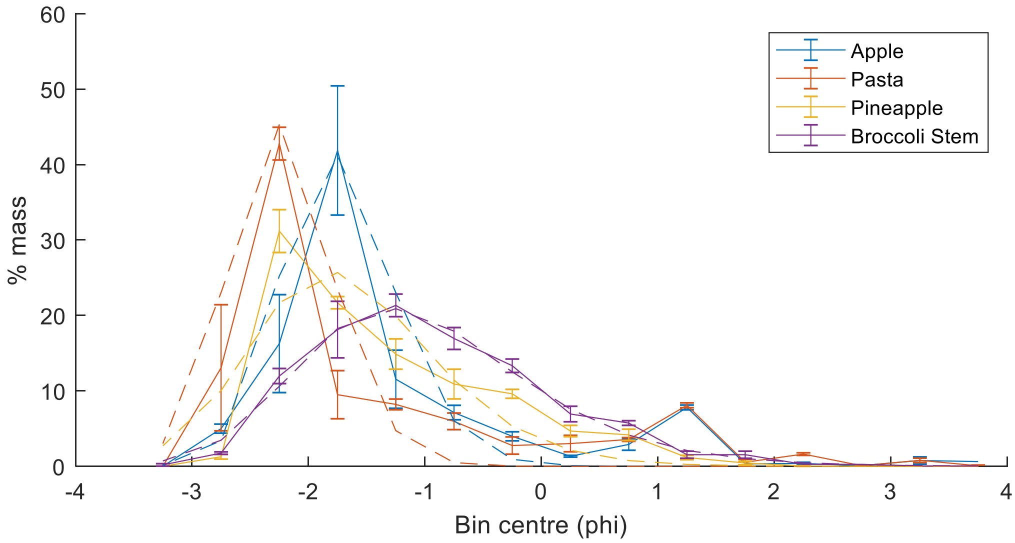

Figure 5 Gamma distribution fitted to four food types showing the best (broccoli stem) and worst (pasta, Pineapple, Apple) fitting cases. Solid lines are measured data. Error bars are standard deviation of repeated measurements. Dashed lines are fitted Gamma distributions. Note: Phi is a logarithmic scale; a small phi value indicates a large sieve size (e.g. -3phi = 8mm) and a large phi value indicates a small sieve size (e.g. 4phi = 0.0625mm)

2.3.2 Maximum settling velocity

Figure 6 shows the settling velocity of each food type as a function of each particle size fraction, while Figure 7 shows the cumulative mass percentage by maximum settling velocity. The maximum settling velocities for all food types, except egg shell, were below 0.1 m/s. Fruits, vegetables, meat/fish, pasta, and cheese were all well below 0.1m/s, with grains such as rice and pasta showing slightly higher maximum particle settling velocities. The clear outlier was egg shell which showed maximum settling velocities over 0.1 m/s for many particle sizes and for the largest particle sizes up to almost 0.13m/s. This is due to the density of eggshell being greater than the other foods as it is mineral based. The relationship between particle size and settling velocity is not as linear for eggshell as the other foods and this could be due to the particles more significantly deviating from spherical the larger they get and they exhibit more plate-like characteristics by floating down. This results in the maximum settling velocity not correlating to the maximum particle size and is due to the larger particles being shell fragments.

For some foods the maximum settling velocity of particles within some sieve sizes could not be measured as the number of particles collected from this fraction was too low to enable measurement. The standard deviation between repeated measurements of particle fall velocity was calculated for size fractions of each food type. Averaged across all sizes and foods, the standard deviation of the particle fall velocity was around 4mm/s within a size fraction. Generally, the standard deviation of the maximum particle fall velocity within a size fraction averaged across each food type was below 5mm/s, except for chicken carcass (7mm/s), white bread (9mm/s) and egg shell (11mm/s). This is likely due to the complex nature of chicken carcass (mixture of bone, sinew, flesh etc.), variability of white bread size fractions (see Figure 4) and the larger measurement uncertainty for egg shells, possibly due to the particle shape and also as the fall velocity was much higher than for other foods.

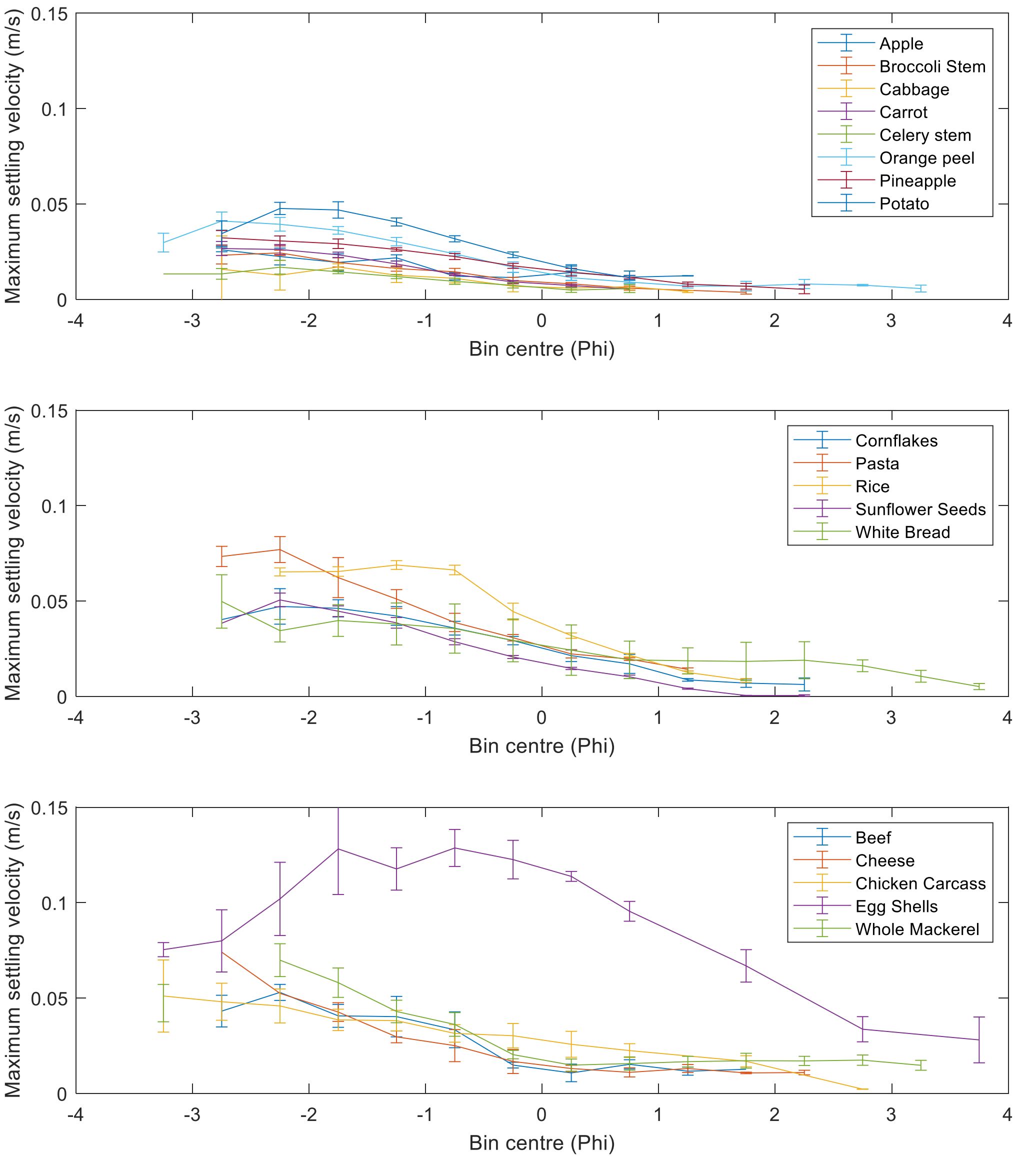

Figure 6 Maximum settling velocity by particle size for all food types, (a) fruits and vegetables, (b) staples and grains, (c) meats, fish and dairy. Note: Phi is a logarithmic scale; a small phi value indicates a large sieve size (e.g. -3phi = 8mm) and a large phi value indicates a small sieve size (e.g. 4phi = 0.0625mm)

Figure 7 illustrates that egg shells, ground pasta and rice are likely to provide the food particles with the highest likelihood of deposition. It can be seen for all three food types that the majority of the ground food has high maximum settling velocities. This indicates that rice, pasta and especially egg shells, are the food types that need to be examined for the risk of deposition in downstream sewers.

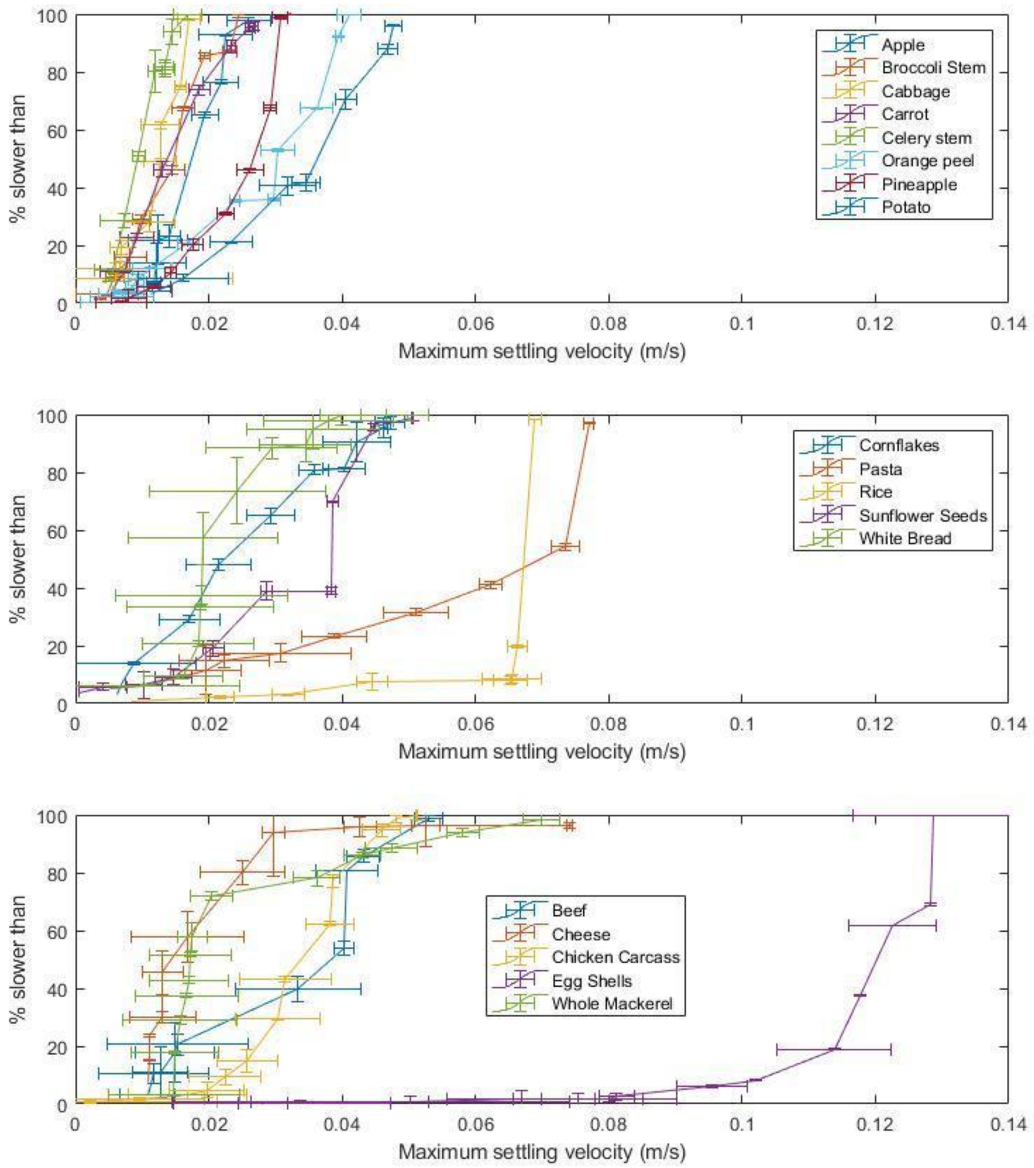

Figure 7 Cumulative mass percentage by maximum settling velocity

2.3.3 Particle transport potential

The data of particle density, indicated that for all the studied food types except egg shells, the particle densities ranged from 1006 kg/m^3 to 1059 kg/m^3 (Table 5). Only the egg shells indicated a higher density of around 1165 kg/m^3. Using the d_{95} values and the particle density values it was possible to estimate a boundary shear stress

(τ_{crit}) that would entrain the maximum particle sizes for each food group using the widely used Shields equation – Equation 8. As can be seen in Table 5 these boundary shear stresses (estimated using a conservative value of Shields Number of 0.065) ranged from 0.01 to 0.15 N/m^2, values that would be commonly encountered in many foul and combined sewers during dry weather flow. Only the egg shells with an apparent particle solid density of 1165 kg/m^3 required a boundary shear stress of 0.38 N/m^2, a significantly higher value. It was decided to examine the entrainment behaviour of egg shells in more detail for two reasons (i) it is the food group that has a significantly higher shear stress threshold than all the other food groups; (ii) visual inspection indicated that the egg shell particles were not spherical in shape and so weaken the assumptions used in Equation 6 and Equation 7.

Table 5 Apparent particle density for the largest practical particle sizes of FWD derived particles for 18 food groups and the estimated entrainment threshold shear stress value

Food Type	d95 (mm)	V95 (m/s)	ρs (kg/m3)	τ_{crit} (N/m^2)
Apple	5.69	0.026	1006	0.02
Beef	5.79	0.043	1015	0.06
Broccoli Stem	5.17	0.024	1006	0.02
Cabbage	7.11	0.017	1002	0.01
Carrot	4.68	0.026	1009	0.03
Cheese	2.64	0.04	1049	0.08
Celery stem	4.74	0.016	1005	0.02
Chicken Carcass	5.65	0.048	1022	0.08
Cornflakes	3.26	0.047	1046	0.1
Egg Shells	3.59	0.111	1165	0.38
Orange peel	6.59	0.037	1011	0.05
Pasta	7.1	0.073	1033	0.15
Pineapple	4.48	0.031	1015	0.05
Potato	4.86	0.041	1021	0.07
Rice	2.79	0.043	1051	0.09
Sunflower Seeds	3.91	0.05	1040	0.1
White Bread	2.28	0.039	1059	0.09
Whole Mackerel	7.88	0.05	1015	0.08

Erosion meter tests were conducted for egg shell particles as described in Section 3.6. The shear stress observed to entrain deposited egg shell particles is shown in Figure 8 and is higher than estimated and reported in Table 5. Error bars on the data indicate the maximum and minimum shear stress measured for repeated tests. While the apparent density of egg shell based in its settling velocity was 1165 kg/m, direct measurements of egg shell density by Carter (1968) indicate that the density of egg shell is 2241 kg/m^3 $^+/_-$ $4kg/m^3$. If this value is used with the estimated shear stress from the erosion meter tests, it can be seen that the Shields number (Equation 8) is close to 0.065 on average (threshold for sustained particle movement), varying non-linearly from 0.036 to 0.078 depending on particle size, and suggesting that the shape of the egg shell particles at the different size fractions may also have an effect on their entrainment. Larger egg shell particles are observed to have a plate-like shape with lower sphericity. This leads to a larger deviation from spherical behaviour for the larger particles. Error bars are also larger for larger particle sizes due to the plate-like behaviour and the larger size intervals. It should also be noted that at all size fractions the shear stress required to mobilise egg shell particles was lower than the shear stress required to move equivalent sized sand particles.

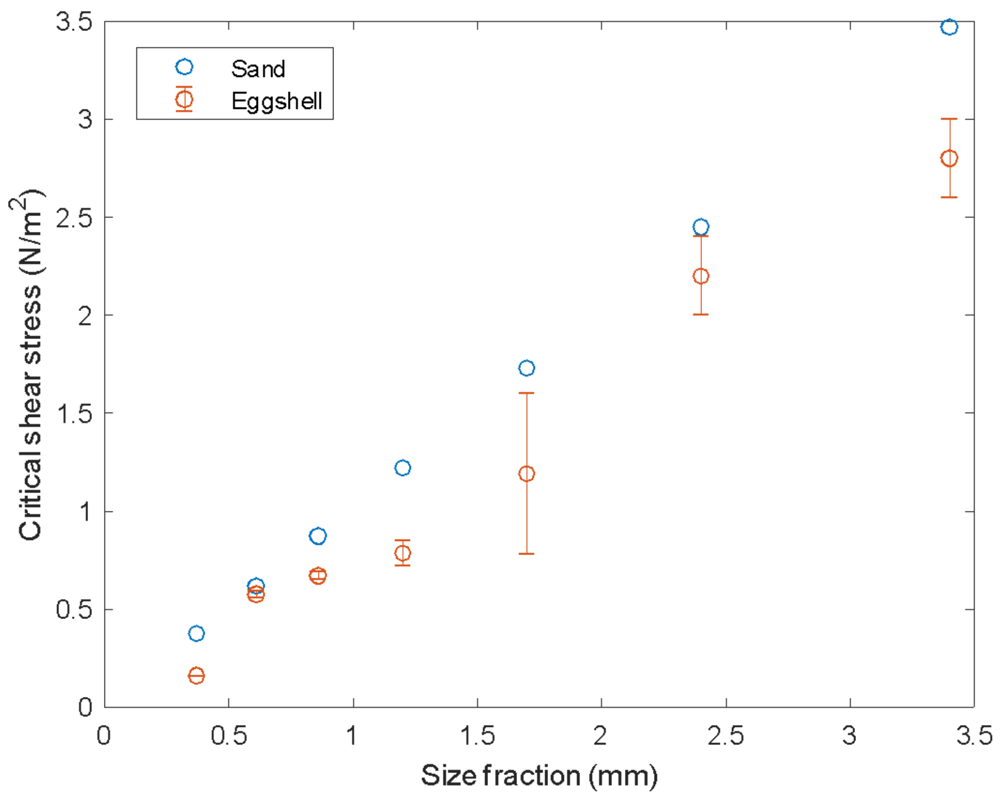

Figure 8 Egg shell mobility

2.3.4 Discussion

The tests reported here are intended to contribute to the better understanding of the nature and potential behaviour of FWD derived particles and the implications of their input into sewer systems. The careful testing and clearly defined and followed protocols for examining individual food types provide scientific robustness and confidence that the results are both repeatable and realistic.

Careful laboratory testing has provided detailed descriptions of particle size distributions (psd) at ½ phi intervals for ground food waste from a single FWD model for 18 food types that are commonly found in the UK. These psd descriptions have a single mode, with a range of modal sizes and widths of the distributions. The shape of the particle size distributions is repeatable for particular food types but there are no clear similarities among food types within a given food group. The distributions were described well by Gamma distributions, which agrees with other studies of granular and ground materials.

Samples from the individual size fractions were collected and the maximum fall velocity was determined for each particle size fraction. This chapter has demonstrated that the highest fall velocities were found for pasta, rice and egg shell. The shape of the mass distributions for these food types showed that significant amounts of each had fall velocities above 0.06 m/s.

The values of maximum fall velocity did not link directly with particle size for different food types, indicating a variation in particle density. Taking the maximum practical size fraction (d_{95}), its fall velocity and assuming the particles were spherical, it was seen that there was a variation in particle density, and that for 17 out of the 18 food types these values were close to the density of water. One food type, egg shells, indicated a higher density and this food type was subjected to further investigation.

The detailed particle size distributions measured correspond with the limited particle data obtained in earlier studies (Kegebein, et al., 2001; Galil & Shpiner, 2001; Channon, et al., 2013; Drinkwater, et al., 2015), although the data from these studies were generally of very low resolution so an objective comparison is difficult. The study by Drinkwater using cooked food appears to be an outlier with this and other studies with regard to the particle size distribution of ground food waste, generally showing larger particle sizes.

Analysis using the maximum practical size fraction (d_{95}) for all the food groups indicated that the boundary shear stress needed to entrain FWD particles was low in comparison to boundary shear stresses found in most foul and combined sewer pipes. For egg shells further tests indicated that the boundary shear stress required to entrain these particles is considerably higher than for FWD derived particles of other food types, most likely due to the higher density and likely also affected by lower particle sphericity. It is clear that particle density is the most important particle parameter in determining the entrainment threshold for FWD particles. Whilst the likelihood of egg shell settling is higher than other food types, egg shell deposits can be assumed to be moved by normal peak dry weather flows, and nonetheless egg shells only comprise around 1% of the overall mass of food waste so the likelihood of creating significant in-sewer deposition in sewer networks is very low.

2.4 Conclusions

This chapter has shown that for 18 common food types the modal particle size varied between 0.59mm and 4.76mm and the standard deviation varied between 0.34mm to 0.62mm. Particle size distributions are shown to conform well to Gamma distributions, meaning they can be characterised by just two parameters.

Particle densities were estimated using particle size and fall velocity data. This demonstrated that most FWD particles had particle densities close to that of water. This results in these particles being entrained into motion at low values of boundary shear stress. The ease of entrainment means that the vast majority of food types are highly unlikely to form persistent deposits in sewer pipes.

Egg shell particles showed a submerged density estimate considerably higher than the other food types, and thus the entrainment threshold was considerably higher than for the other food types. The deposition risk of egg shells is thus higher than for other food types, however its overall prevalence in waste food is very low (around 1%) so it is unlikely to cause significant practical deposition issues.

This chapter has shown that, by employing the robust experimental method described, the deposition risk of FWD derived particles can be assessed. Further work should expand the range of food types, and explore the implications when applied to flows in a range of sewer systems. The data can be used to assess the transport behaviour of the particles from food waste disposers and estimate, based on the UK food mix (WRAP, 2009) the proportions of different foods by weight in differing modes of transport in the sewer.

3 Assessment of the transport behaviour of food waste disposer derived particles through sewer networks

Chapter Overview

This chapter aims to assess the transport behaviour of the particles from food waste disposers described in Chapter 2. This is done by creating a hydrodynamic network model of the field site, calibrated and validated using flow survey data, to model particle transport. This allows for the risk of deposition of every particle size of every food type to be assessed in every pipe in the sewer. This is further validated by in-field tests. Mode of particle transport is presented and for the "average pipe" in this network, no food particles are expected to settle, with for the 50.6% of the particles measured being in suspension, 46.7% being in saltation, 2.8% being in bedload and 0% settling. Deposition of two particle size fractions of eggshell was identified to occur in one pipe in the network. Saltation is defined as a form of particle movement wherein the particle "jumps" or "hops" along the bed of the pipe, it will spend moments on the bed and will be picked up and carried by the fluid before being dropped on the bed once more. Bedload is defined as the particle movement which occurs on the bed of the pipe and these particles are not picked up in the way that saltating particles are; the bedload remains "rolling" or "sliding" along the bed of the pipe.

3.1 Introduction

Managing domestic food waste is challenging due to the amount of the waste involved and the potential significant environmental and financial impacts. One solution is to divert this waste from a collection and disposal option (landfill/digestion/composting) by using domestic food waste disposers to grind this carbon rich material so it can be transported via existing sewer networks for treatment at existing wastewater treatment plants. This resource can subsequently be made available for anaerobic digesters already in use at many larger wastewater treatment works. However, water utilities wish to understand the risks associated with introducing food waste particles into their sewer systems and also the increased carbon loading on their treatment plants. In this chapter the research will investigate the potential impacts on existing sewer networks caused by the introduction of food waste disposer derived particles. This chapter describes the development of a modelling approach that utilises the data from the particle characterisation studies described in the previous chapter, combined with the simulated hydraulic conditions in a sewer network to predict the transport mode and the risk of settling of food waste. This modelling is used to better understand if there are risks associated with introducing food waste disposer derived food particles. The work has focused on dry weather flow as this pattern poses the highest risk in terms of particle settlement and deposit formation. The focus on dry weather flow means that the results are applicable to both foul and combined sewer networks. The improved understanding and modelling capability is important to help policy makers make informed decisions on food waste disposers as a solution for food-waste management and whether they will create significant performance issues in existing sewer networks.

There are field studies available with qualitative observations of food waste disposer derived particle transport (Mattsson, et al., 2014) and a long-term study at Surahammar reported by Evans et al. (2010) . These studies have both indicated that FWDs have a minimal impact in-sewer. Mattson used CCTV to monitor deposition in sewers and to see if levels of deposition correlated to levels of FWD installation upstream. FWDs were shown to have a minor impact on deposition – the deposits visibly contained eggshells and this type of particle was mostly absent from pipes that did not have FWDs upstream. Food waste did appear to accumulate around existing sewer blockages, but it was not possible to determine if these were persistent or not. Little detail was given of the possible hydraulic conditions in the network. In the Surahammar long-term study, 15 years of sewage treatment works monitoring data was evaluated to determine the impact of FWD installation and there were also video inspections of pipes, even with slopes as shallow as 0.001, where no deposition of food waste was observed.

Qualitative information is an insufficient basis for development of an understanding that can be applied generally to determine the risk of sewer blockages in any network. In this chapter a modelling methodology is developed and applied to a small foul network and the simulation results are validated with particle transport observations. The risk of blockage in this network is estimated and the protocol developed in this chapter can be applied to other sewer networks.

3.2 Method

3.2.1 Assessment of Blockage Risk

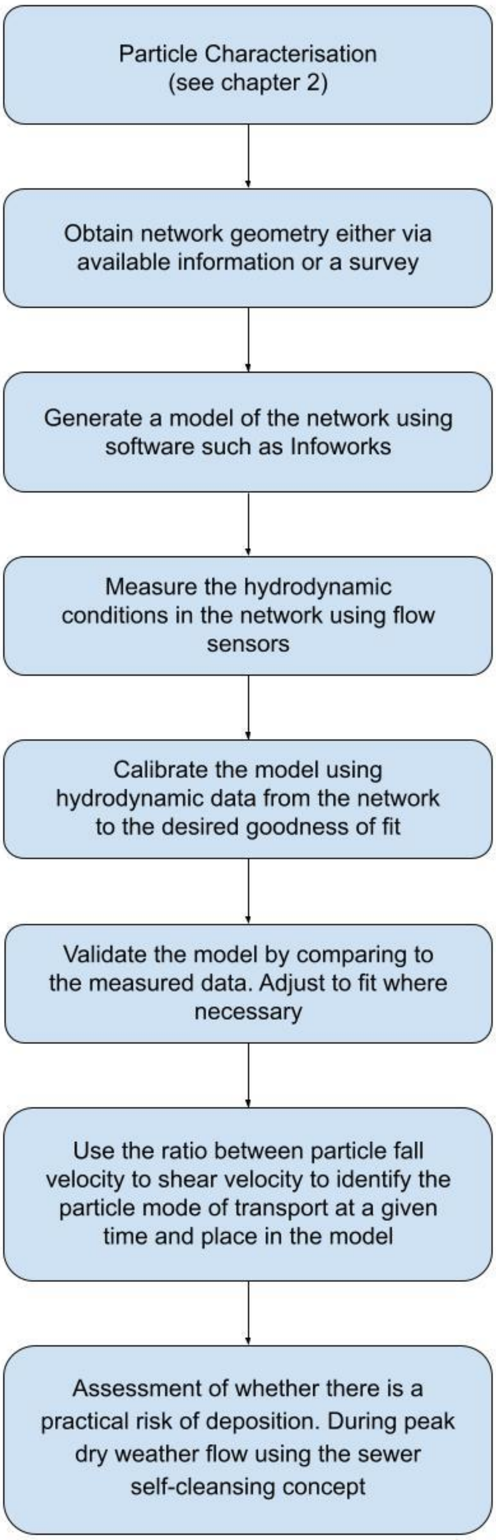

Figure 9 A flow chart outlining the assessment of particle transport

In order to assess the blockage risk within a network during dry weather flow, a calibrated hydrodynamic network model should be created as each network has different spatial and temporal patterns of in-pipe flow. The goodness of fit should be such that the diurnal flow pattern should match up, the total volumes should be consistent between modelled and measured data, and that flow rates and depths should also be consistent with no big variation between modelled and measured data. The use of this model should focus on periods of low flow during which the potential of deposition of moving food waste disposer derived particles could be high and also periods of peak flow in which the majority of food waste disposer particles are likely to be introduced at multiple locations into any sewer network. Deposition risk and transport mode are estimated based on existing sediment transport mode relationships, using the hydraulic conditions at specific locations combined with the experimentally measured food waste disposer derived particle characteristics described previously. Understanding the transport mode at times when particles are introduced and during daily periods of peak dry weather flow will allow the deposition risk for different food particles to be assessed for different systems.

The assessment method has been developed (Figure 9) and validated in a small foul sewer network, in which it is know that significant numbers of food waste disposers had been installed.

3.2.2 Creating a hydrodynamic network model

When creating a hydrodynamic network model, it is necessary to mimic the real world as closely as possible. In this case a network model of the Upper Rissington foul sewer network was created. As laid plans of the sewer network were obtained from the water utility company (Albion Water) and were used to create the model geometry. To calibrate the model and validate its predictions a flow survey was commissioned from Environmental Monitoring Solutions (EMS) so that the collected flow data was being used to create a calibrated model. During the calibration special focus was given to peak flows in DWF periods. The benefit of this is that a much more appropriate model is created to study food particle behaviour.

The project investigated a sewer network and linked WWTP in the South-West of England at Upper Rissington (Figure 10). The sewer network and WWTP serves approximately 500 households. Upper Rissington is comprised of two distinct areas;

one is the original residential area, with an older combined sewer network (serving around 260 properties), and the other is a new build residential area which is a, a new downstream development with a new build separated system (serving 242 properties) with separate foul and stormwater sewers. It is known that the developer of the new residential area has installed 150 FWDs in the majority of the new properties. The older combined network feeds into the new network in two places (a third feed from the older combined network goes directly to the treatment plant). The new network feeds directly into the WWTP. The focus of the research is into food waste derived particle deposition and transport behaviour in the new part of the network.

Figure 10 Aerial photograph of the Upper Rissington field site. The original residential area, new-build area residential area, which is the area being hydraulically modelled, and the linked wastewater treatment plant is highlighted

To be able to assess the risk of deposition of particles from FWD derived food waste in each pipe of a sewer network, it is necessary to know the hydraulic conditions in each pipe in the sewer network during a 24-hour dry weather flow period. In practical terms, this means creating a hydrodynamic network model of the sewer network as it is not usually practicable to measure hydraulic conditions in every pipe of a network.

In a model it is possible to obtain the predicted hydrodynamic conditions for every pipe. For Upper Rissington, a hydrodynamic network model has been built and calibrated and then used to predicted shear velocity for each pipe for a 24h period. Only flows in the foul network serving the new development has been modelled as this is the area in which FWDs are installed.

Pipe geometry data from as laid pipe plans provided by Albion Water were used to build a pipe network model for the new build residential area in Infoworks CS 12.5. The modelled network has 91 pipes with pipe diameters of 100mm, 150mm and 225mm, pipe lengths ranged from 4.4m to 80m with an average length of 30.7m, and slopes ranging from 0.0043 m/m to 0.15306 m/m and an average slope of 0.0233 m/m.

Table 6 A list of the number of properties allocated to each node with a waste water profile attached to it in the Infoworks CS 12.5 model of Upper Rissington. The nodes that have the wastewater profiles from the old part of the network are attached and these 3 nodes represent the wastewater from a total of ~260 properties beyond the new development in the model. All wastewater profiles are made from measured hydraulic data during the flow survey of Upper Rissington, thus the profiles are representative of the area.

Node ID	Number of Properties	Node ID	Number of Properties
F48	18	F5	3
F50	15	F7	3
F15	11	F8	3
F28	11	F9	3
F47	11	F92_2	3
F35	10	F145	2
F148	8	F155	2
F36	8	F156	2
F14	7	F20	2
F16	7	F22	2
F34	7	F25	2
F43	7	F26	2
F93	7	F40	2
F30	6	F62	2
F44	6	F142	1
F52	6	F143	1
F146	5	F144	1
F153	5	F24	1
F154	5	F3	1
F27	5	F39	1
F46	5	F41	1
F10	4	F92	1
F151	4	F94	1
F17	4	F95	1
F19	4	F97	1
F23	4	F140/ inlet from old	Wastewater Profile
F38	4	F152_2/ inlet from old	Wastewater Profile
F42	4	F92 / inlet from old	Wastewater Profile

Of the 92 nodes in the network model, 53 nodes have properties attached and 3 nodes have wastewater profiles which represent the ~260 houses from the old part of the network. As shown in Table 6, the number of properties attached to each node range from 1 to 18. As the site used in the model is a new build development there is no census population data and the new properties that have been built are not comparable to the existing old development so it would not be possible to extrapolate population data. Due to this, it was decided to distribute the flow on a per property basis, rather than a per person basis. Whilst the properties in the old part of the network do not have FWDs installed, it is unknown where every FWD is located in the new part of the network.

3.2.3 Flow survey of the Upper Rissington Field Site

Environmental Monitoring Solutions is a company specialising in environmental data acquisition and monitoring in sewer networks. For this project they were responsible for carrying out a short-term flow survey on the Upper Rissington sewer network and provided the equipment and personnel to install the flow sensors in the network.

The flow survey collected data from February 1st 2018 until March 15th 2018. Flow depth and flowrate data during working days, Monday to Friday, was used to calibrate the model as the daily household routine is less variable on these days and a more consistent diurnal flow is observed. The later observations of food particle presence, made from the 10th to the 13th of June 2019, were also made during working days.

In an ideal scenario we would install as many sensors into the sewer network as we could fit to get the most accurate hydraulic information for every single pipe, however, in reality one has to consider budget and resources. This means sensors have to be placed in critical locations where they will collect as much useful data as possible. In this particular network sensor placement was organised into a number of branches and by careful placement of sensors, it was possible to calculate daily flow volumes in branches without sensors via calculation of collected data.

Sensors were placed to capture flow as shown in Figure 11, using the minimum number of sensors possible while still being able to characterise the daily flow volume for each branch of the network. It was critical to have a sensor on the inlet to the waste water treatment works to validate the other sensor readings as this sensor captures the total network flow. In total there are 7 sensors; 3 measuring in the new part of the network, 3 measuring the inflows from the old part of the network, and 1 at the inlet to the WWTP.

Considering Figure 11, the Blue Zone has 14 houses and a block containing 18 flats. a school, some small shops and a combined flow inflow from the old part of the system at node location F94. As the shops and the school could not have their own flow sensors installed, the flow generated from these will be distributed amongst the residential properties in this zone. The flow for properties in this zone is calculated by subtracting the sensor data at F92 from the sensor at point F94, which is measuring the total flow, including the input from the old network at F92, from the blue zone.

The Orange Zone is exclusively residential with 106 houses and the flow rate is calculated by subtracting the flow measured at locations upstream of nodes F94 and F96 respectively. No properties are connected to nodes F53 or F95 which makes it easier to calculate the flow from the orange zone.

The Green Zone is exclusively residential with 85 houses and flow rate and depth is measured using a sensor located upstream of node F30. No calculations are needed as there is a clear boundary and the flow for this zone is measured directly.

The Purple Zone is exclusively residential with 37 houses and has two combined sewer flow inputs, one is upstream of some properties at F140, in the pipe F140>F141, and the other is downstream of all properties, just before the inlet to the WWTP at F152_2. The flow from this zone is calculated by subtracting the measured flow rate from the flow monitors located at F140, F152_2, F30 (Green Zone) and F96 (Blue and Orange Zones combined measurement) from the reading at the WWTP inlet at F152_3.

The locations of the 7 flow rate and depth sensors and the pipe layout and key model characteristics are shown in Figure 11 with the sensor locations described in Table 7 and in Figure 12 the nodes that have properties attached to them are highlighted and it can be seen that the pipes toward the end of the network do not have properties attached.

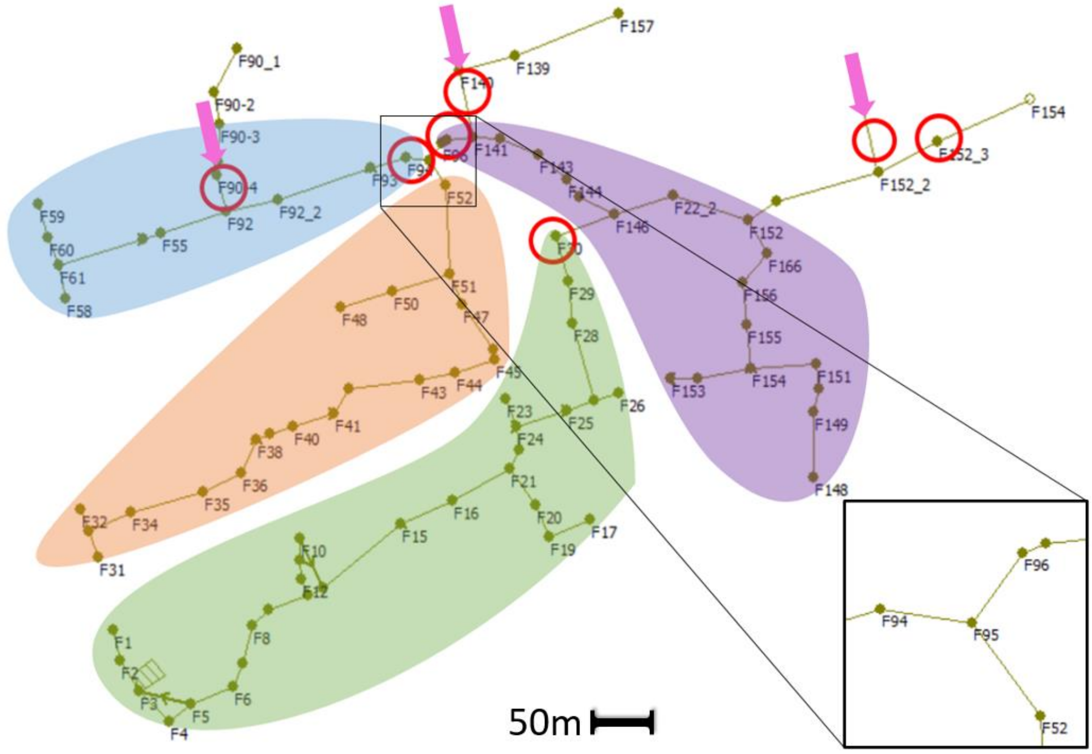

Figure 11 Plan view show the location of flow velocity and depth sensors (red) and the 4 zones; blue, orange, green and purple, of the residential area (total 242 properties). The flows from the old network are measured by 3 sensors at points F94, F140 and F152_2

Table 7 Location of sensors in the network

Sensor ID and node of installation	Pipe ID	Purpose
F140	F141 > F140	Measure the flow coming from the old network
F152_2	woodland pipe > F152_2	Measure the flow coming from the old network
F152_3	F152_3 > F154	Measures the flow at the inlet to the WWTP
F30	F30 > F146	Calibrate the daily flow volume in the new network
F92	F90-4 > F92	Measure the flow coming from the old network
F94	F94 > F95	Calibrate the daily flow volume in the new network
F96	F95 > F96	Calibrate the daily flow volume in the new network

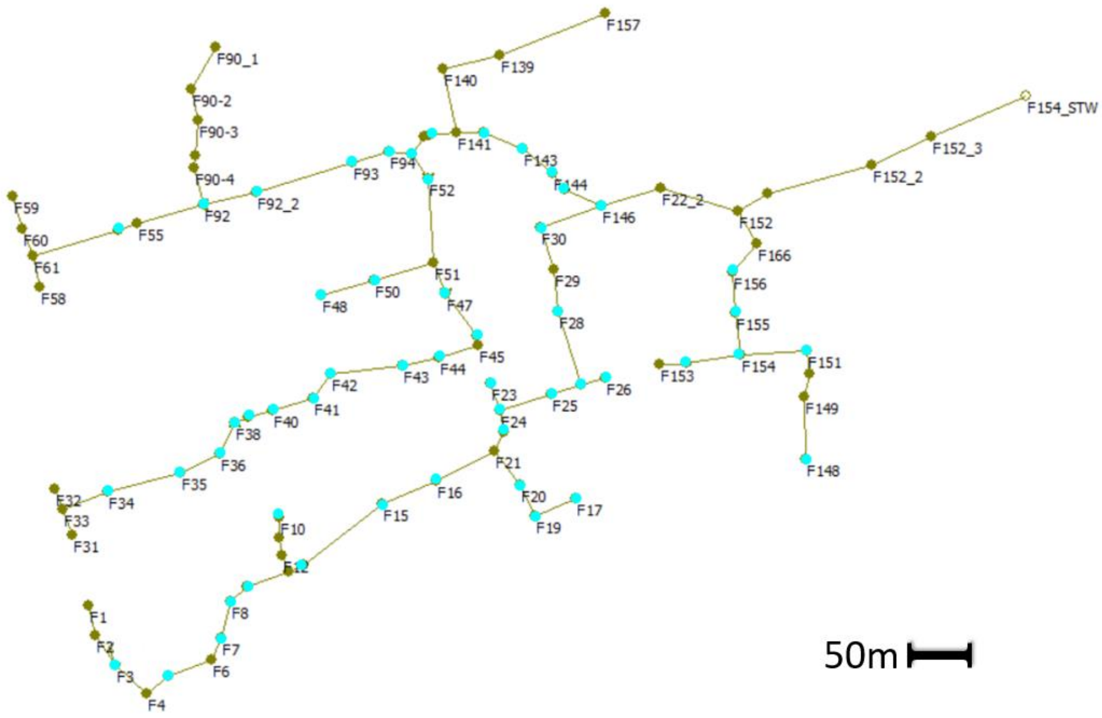

Figure 12 Plan view of the network where nodes that have properties attached are highlighted

For the purpose of the study, DWF is used. This is because it represents the “highest risk” type of flow pattern for any potential deposition and also as the new sewer network is a separate system, with both foul and storm water sewers, the newness of the system means that it was assumed that there would be minimal infiltration. However, the old network feeds directly into the new network at 2 nodes and also after the new build area there is a third input from the old network joins shortly before the inlet to the WWTP. The old network is a combined system that was built in the 1930s so may be influenced by infiltration and wet weather events. If the new part of the network can be effectively self-cleansing at DWF, then the likelihood of operational issues resulting from food waste derived blockages is low. As the target is DWF, this means that no wet weather events are needed to be captured and a relatively short flow measurement campaign can be undertaken with data being taken from days with no rainfall. DWF is defined as a day with less that 1mm of rain on the day and in the preceding 2 days. The rainfall data was provided for the duration of the sewer monitoring activities by Albion Water, the water utility company responsible for the network, and the location of the rainfall gauge was at the WwTP

(F154_STW on Figure 12). The data was collected by Albion Water and shared with the University of Sheffield for the purpose of defining dry weather flow days.

Flow data was collected for a total of 6 weeks and was manually collected and reviewed every two weeks. An issue was that the flow was low due to the small catchment, which poses a technical challenge as the sensors at F30, F92, F96 and F140 suffered from velocity drop outs. Sensor F94 required recalibrating to pick up flow on the first visit and was subsequently replaced on the second visit due to continued issues which allowed for data to be obtained for the last part of the survey. There were also ragging events on F30, F92, F94 and F96, causing gaps in the data and in the event of wet weather, the data from those days could not be used as they would be noticeably affected by the combined flow incoming from the older network. Despite these challenges, data was collected from all sensor locations allowing for calibration of the new part of the network.

To get a representative dry weather diurnal profile, three 24h profiles were chosen based on them being 3 consecutive days which appeared to be consistent with each other across that three-day period. The 3 days were then averaged together to get a single averaged 24h profile. This was done for each sensor location. Only week day profiles and days during dry weather, defined as a day with less that 1mm of rain on the day and in the preceding 2 days, were chosen and this data was then used to calibrate the model.

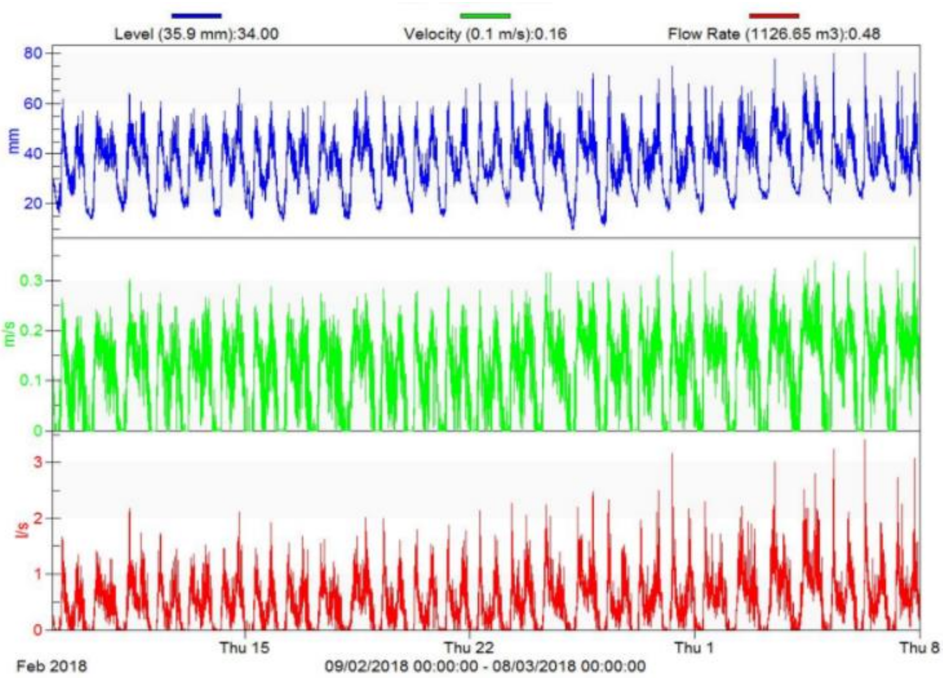

Figure 13 Example sensor output data, from manhole F92 with the sensor in the pipe with upstream node F90-4, showing depth (blue), velocity (green) and flow rate (red)

3.2.4 Calibration of the Hydrodynamic Model

To have confidence in the model, it is necessary to check that everything is consistent and that the modelled flow is not drastically different from the measured flow. Whilst they will not be exactly the same due to the modelled flow being equally distributed according to property numbers due to the absence of population data such as a census, when in reality different properties will be contributing differently.

Infoworks CS v12.5 is used to create the hydraulic network model as it is possible to transfer the as-laid plans to a digital twin of the sewer network and allocate a range of inflow conditions throughout the network based on the output of the flow survey. The model uses a minimum base flow depth of 0.005m, a timestep of 7.5s, a steady state tolerance of 0.002m^3/s and has a Colebrook-White pipe roughness of 2mm, which is suitable for pipes in a newly built network (Wallingford & Barr, 2006). These parameters were amended from the initial parameters for the model and allowed for consistent simulation results.

The new build area, is divided into 4 sections (Figure 11) and the first iteration of the model runs was modelled using diurnal flow profiles directly created using a 3 day average from 3 days consecutive DWF days at a lower resolution of 20 minute time steps. This comprises of the shape of the profile and the daily flow volume per property: this will be referred to as the original wastewater profile.

The key parameters in the model are the daily flow volume and the shape of the diurnal profile. The diurnal profile is presented as a factor and this dictates how the daily flow volume is distributed over the 24h period. If the shape of the diurnal profile is altered, by changing one of the factor values, this does not change the daily flow volume – the area under the diurnal profile stays the same, it is just the shape that is altered and the daily flow volume is distributed accordingly. Similarly, changing daily flow volume does not change the shape of the daily profile, it just dictates the area under the curve.

The dates chosen were not the same for each sensor location due to issues with fouling during the measurement campaign, so it was not possible to have the same 3 consecutive days with the same dates for each sensor location. This method was used to get the original wastewater profiles for every wastewater profile in the model and these were then altered to improve the calibration. The wastewater profiles are allocated on a per property not on a per person basis, the values in some parts of the network are higher than the CIRIA national average for a household is 420L/day (Ackers, et al., 1996), however, this is what was measured in the network.

The following described amendments all are in reference to the original wastewater profiles created for the first iteration of the model. The amendments are described in full and done so that the model output better matches the measured data. The comparison between the model output and measured readings presents the final model data.

For the green zone (Figure 14), the model output had very high peaks in both the morning and the afternoon in the first iteration of the wastewater profile when compared to measured data. This suggested the input wastewater profile's diurnal peaks needed lowering and so both peaks, had these points reduced by 60%, the morning peak from a factor of 4.607 to 1.843 in the wastewater profile and afternoon peak from a factor 4.231 to 1.692.

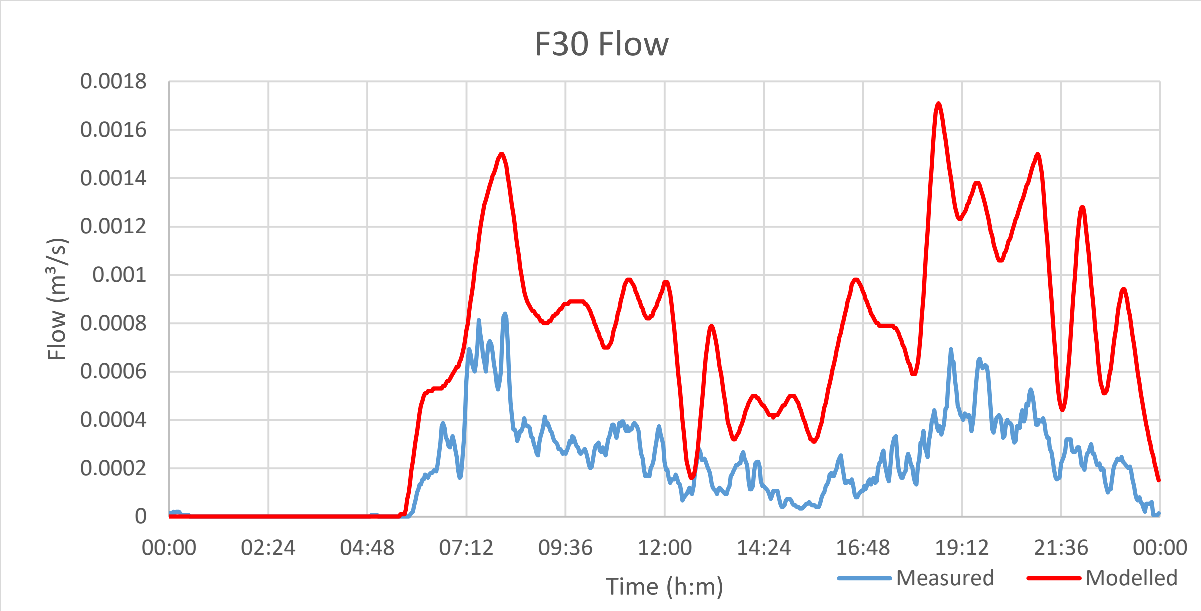

Figure 14 Modelled and measured outflow from the Green Zone (Monitor F30)

The orange zone (Figure 16) was not directly measured so the wastewater profile was generated from subtracting the flow data from F94, which took the houses from the blue zone plus the input from the old network at F92, from the flow data at F96, which took the flow from both upstream of F94, plus the whole orange zone. By removing the F94 flow from the F96 flow, what is left is the flow contributed by the orange zone. The wastewater profile for this zone had the profile shifted 1h earlier in the day (so instead of the main morning peak starting around 8am, it now starts at 7am), the morning peak value reduced by 25%, from a factor of 2.972 to a factor of 2.229 and the total volume lowered by 38.9% from 3276 l/day to 2000 l/day.

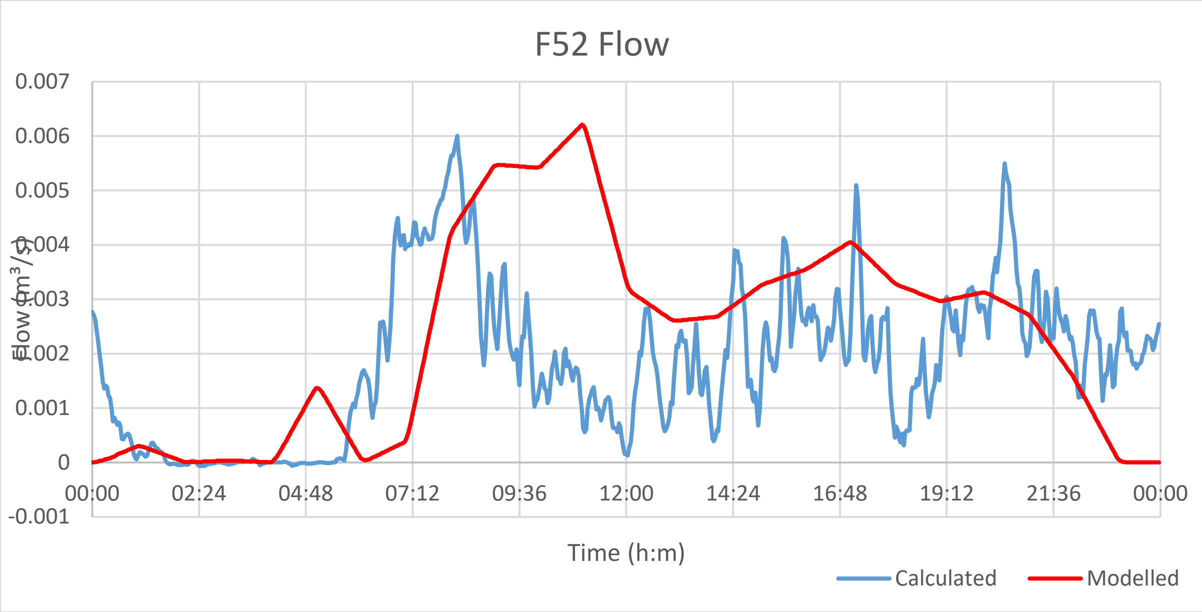

Figure 15 Modelled and calculated outflow from the Orange Zone (Subtraction of Monitor F94 and F96)

The blue zone (Figure 17) had the total volume for its wastewater profile increased by 30% from 3270 l/day to 4251 l/day as the modelled flow from the original wastewater profile was much lower than the measured flow.

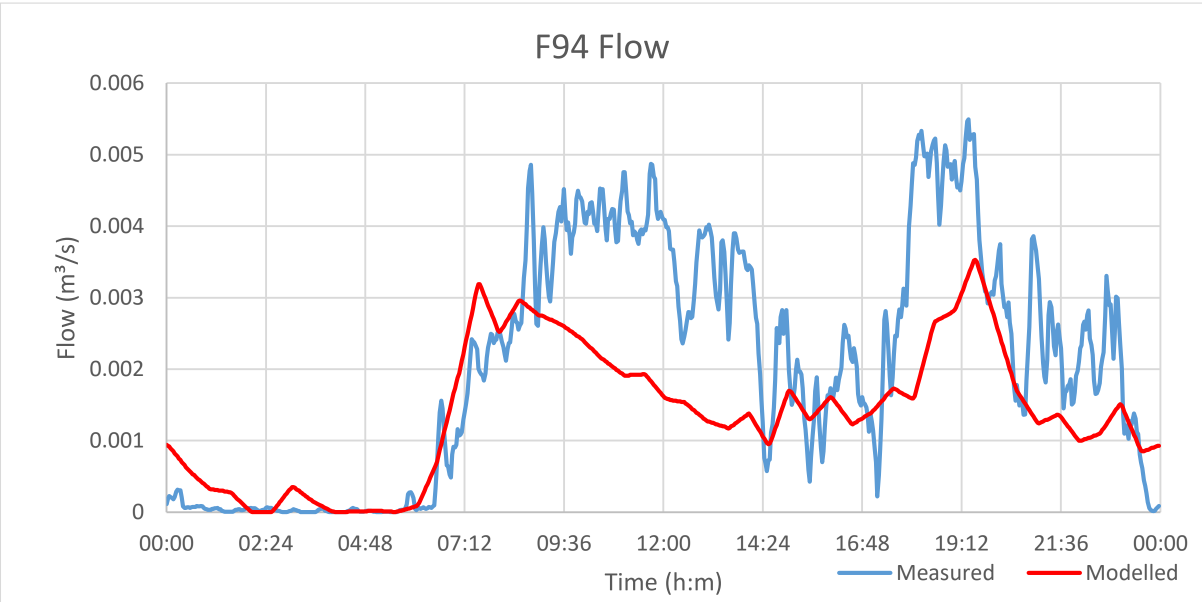

Figure 16 Modelled and measured outflow from the Blue Zone including the input from the old network at F92 (Monitor F94)

The sensor at F96 (Figure 17) shows the combined flows of the blue zone and the orange zone. Due to the recalibration amendments, the measured flow and the modelled flow fit was improved.

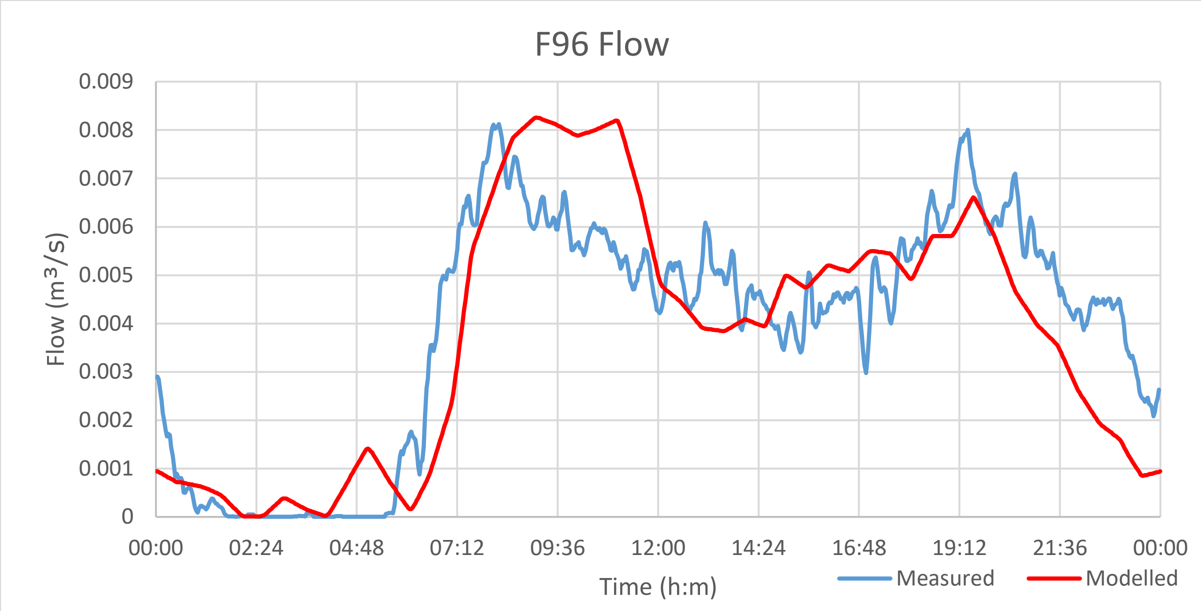

Figure 17 Modelled and measured outflow from the Blue and Orange Zone combined (Monitor F96)

The purple zone wastewater profile was not changed from the original wastewater profile of the model. This wastewater profile was generated by subtracting the following 4 sensor data flows; F30 (Green zone), F96 (Blue and Orange zones), F140 (input from the old part of the network), F152_2 (input from the old part of the network), from the F152_3 flow data (inlet to the WWTP flow). The purple zone contains a small number of houses before the WWTP.

The comparison between the modelled and measured flows at F152_3 Figure 18 shows the cumulative effect of all the input wastewater profiles on the modelled flow profile at the inlet to the WWTP.

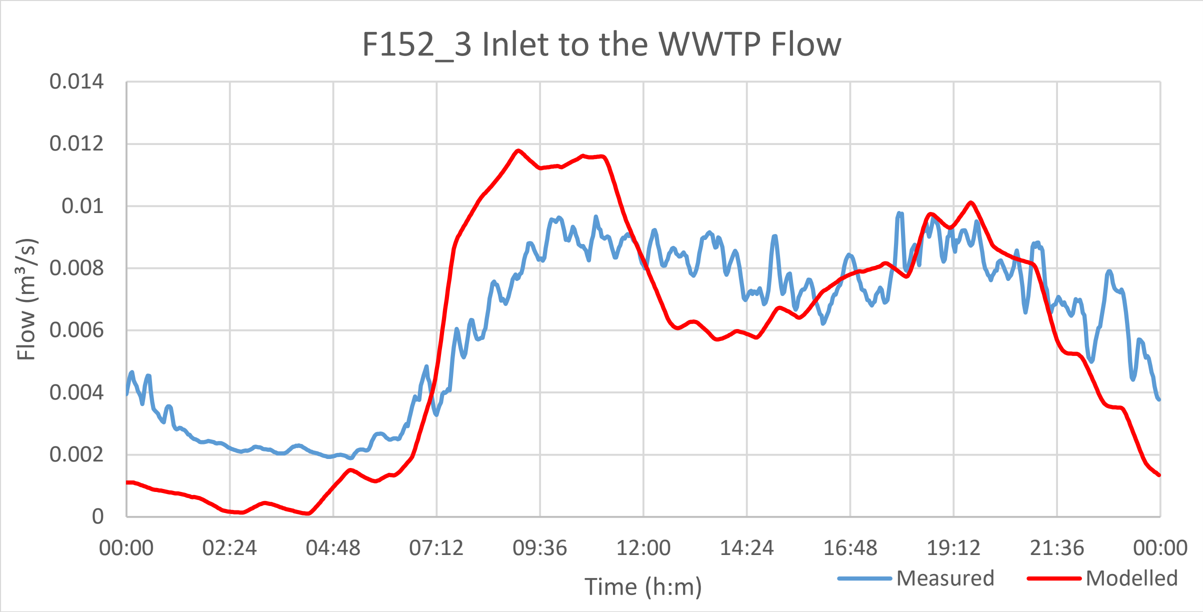

Figure 18 Modelled and observed flow rates at the inlet to the WWTP, which contains all the flows from the blue, orange, green and purple housing areas.

In Table 8 it shows that measured 24h volume of the network was 532.9 m^3 and the modelled 24h volume of the network was 495.5 m^3, which represents the measured volume being 7.5% larger than the modelled volume. Whilst the distribution of modelled volume between the blue and orange zone varies with the measured data by 58.8 and -44.6 m^3 respectively, the difference between measured and modelled data for those areas combined is 12.3 m^3, which is relatively small difference of 3.8%. The green area contributes the smallest volume, modelled at 53.7 m^3 with the measured being 36.0 m^3 less, however, this discrepancy appears to be due to the measured data used for validation being different to the measured data used to calibrate the model which had a volume of 48m^3. Models are only as good as the data put into them, so to improve the model a longer monitoring campaign could be done to determine which of the measured data is more representative.

Table 8- Comparison of modelled and measured 24h total volumes within the network. *[For F95, the flow was not directly measured, but it is possible to calculate the value from subtracting F94 from F96]*

Location	24h Volume (m^3)			Difference	
	Modelled	Measured	Calculated	Total (m^3)	%
F30 (green)	53.7	17.7	-	-36.0	-67.0
F94 (blue & F92 old network input)	120.0	178.8	-	58.8	49.0
F52 (orange)	203.5	-	158.9	-44.6	-21.9
F96 (orange & blue & F92 old network input)	325.4	337.7	-	12.3	3.8
F152_3 (all zones & old network inputs)	495.5	532.9	-	37.3	7.5

3.2.5 Model Validation

Once the wastewater flow profiles had been calibrated for each zone of the network, depth and velocity predictions were checked to provide a validation of the model performance. Validation comes from the comparison of flow, depth and velocity. Validation data comes from a different 3-day average than what was used to calibrate the data.

The measured flow depth and velocity, based off an average of three consecutive DWF days during the measurement campaign, is compared to the hydraulics modelled in InfoWorks CS 12.5. Averaged flow, velocity and depth are compared at the sites that the measurement campaign had sensors installed. A 5 point moving average filter was applied to the raw data from the measurement campaign to remove some of the signal noise.

The flow is compared at the 3 locations within the network and also at the inlet to the WWTP. The pipe diameters at these locations are 225mm for F96, 225mm for F94, 150mm for F30 and 225mm for the WWTP. The smallest size pipe in the model is 100mm.

Across the 3 locations in the network the maximum flow ranges from around 0.001 m^3/s to 0.008 m^3/s with the WWTP having peak flows of around 0.012 m^3/s. The root mean square error (RMSE) for the flow at each location were 0.0013 m^3/s for F96, 0.0012 m^3/s for F94, 0.0005 m^3/s for F30 and 0.0020 m^3/s for the WWTP. RMSE was chosen as it looks at the fit by giving a measure of the error between the modelled and original data. It is a generally good measure, however, it can give unnaturally high RMSE in the event of a time shift, which does not necessarily indicate a bad fit.

The depth at the same points is also compared, with peak depths ranging from around 0.02 m to 0.06 m at the 3 points within the network and 0.04 m at the WwTP. The root mean square error (RMSE) for the depth at each location were 0.020m for F96 (Figure 19), 0.024m for F94 (Figure 20), 0.004m for F30 (Figure 21) and 0.015m for the WwTP (Figure 22). Depth is an important parameter as this is what is used to determine the mode of transport of particles.

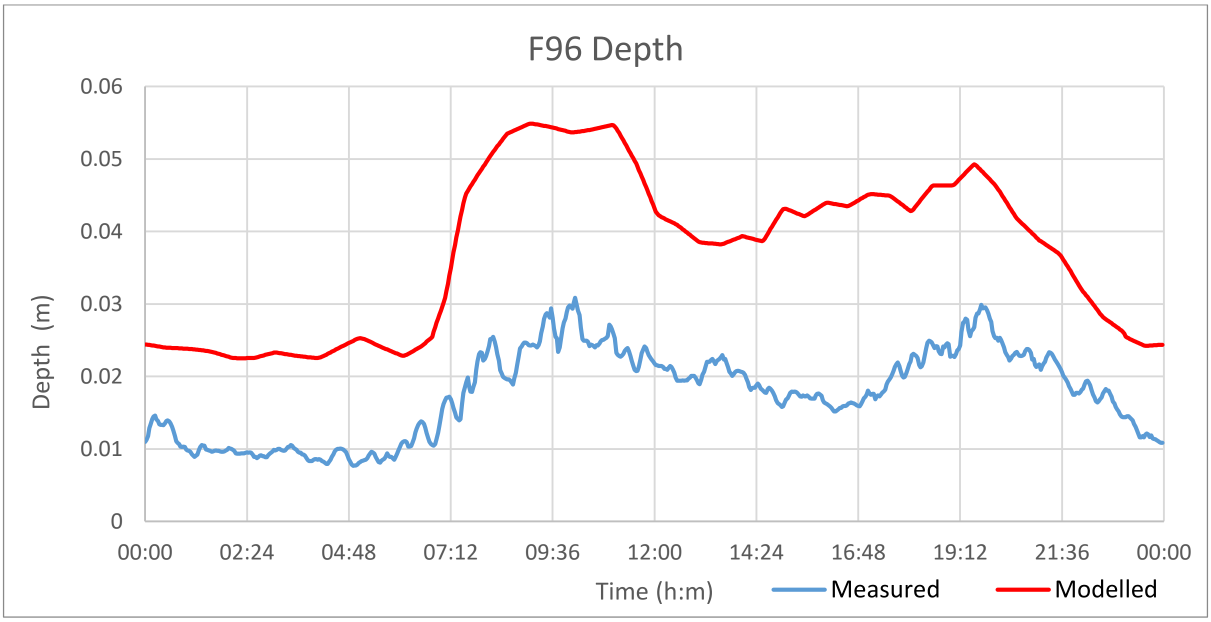

Figure 19 Modelled and measured depth from the Blue and Orange Zone combined (Monitor F96)

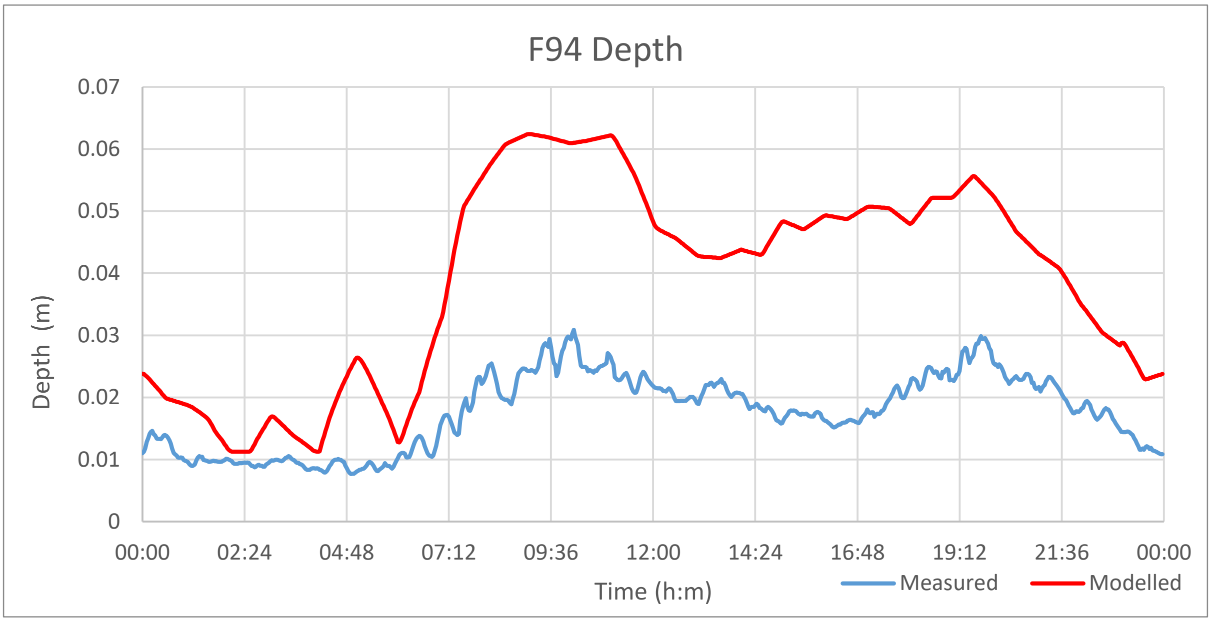

Figure 20 Modelled and measured depth from the Blue and Orange Zone combined (Monitor F96)

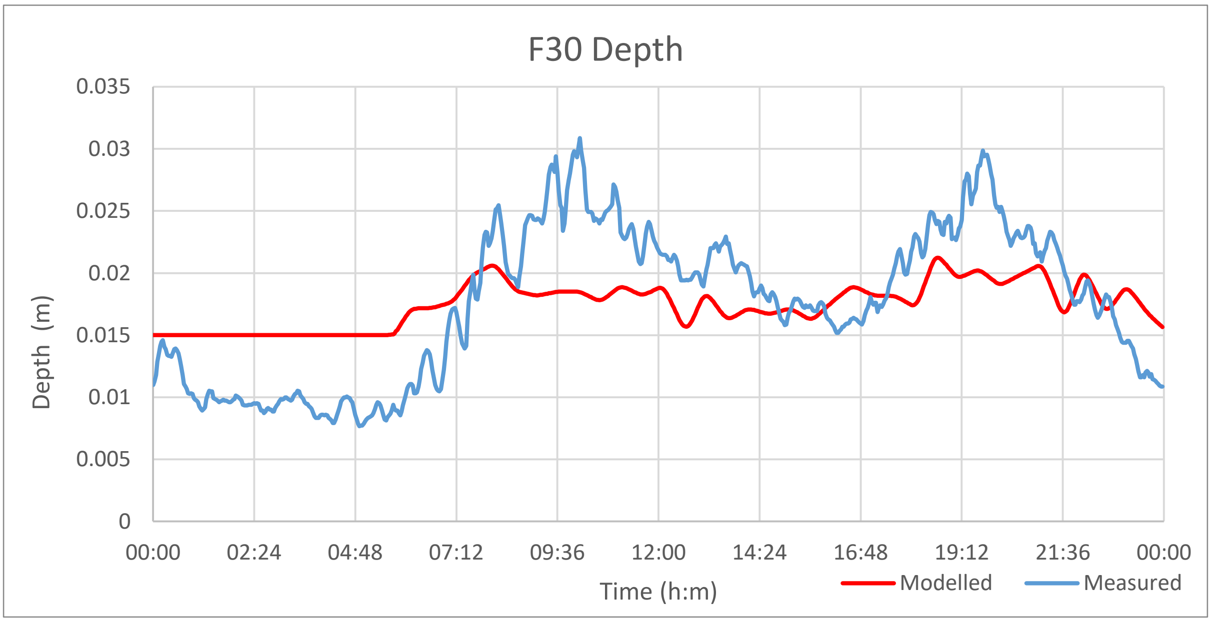

Figure 21 Modelled and measured depth from the Green Zone (Monitor F30)

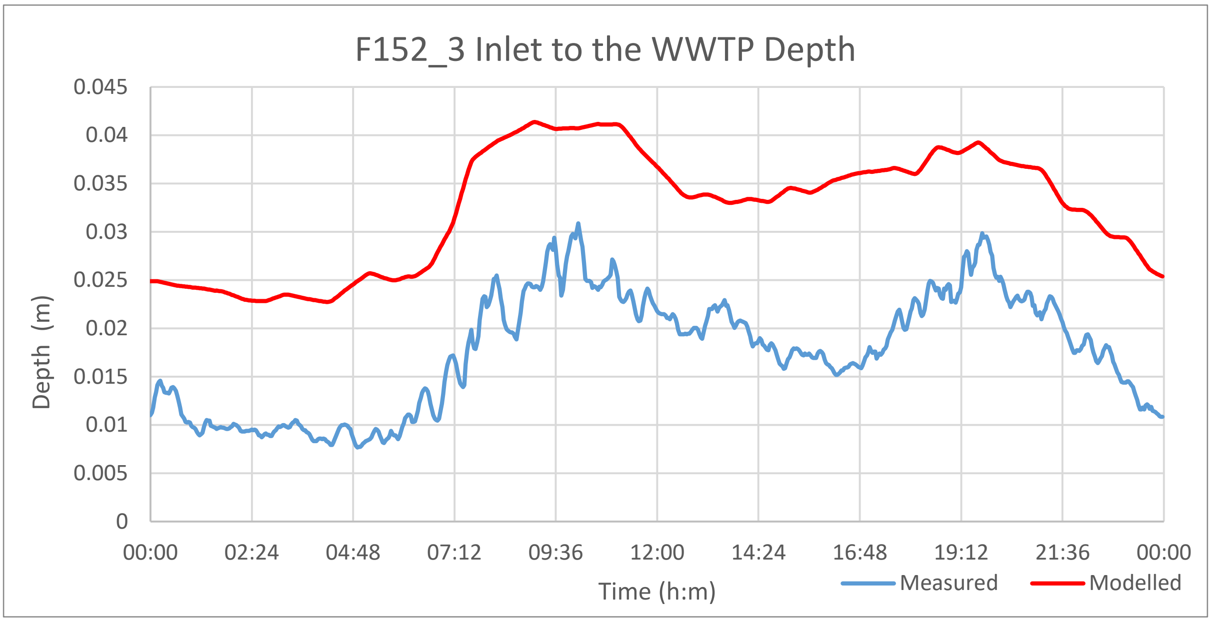

Figure 22 Modelled and observed depths at the inlet to the WwTP, which contains all the flows from the blue, orange, green and purple housing areas.

The key parameter for validating a model is total volume and should always be the first check of any model. Another way to check the goodness of fit is to check if the highest and lowest flows in the model correlate with the highest and lowest flows measured. For future research, the Nash–Sutcliffe model efficiency coefficient (NSE) could be used as this looks at the difference in variance and the series average with values tending to 1 suggesting a more perfect fit between measured and modelled data.

That the depths are higher suggests that either pipe roughness is wrong or that there is a pipe downstream where a mistake has been made creating a constriction. Pipe roughness was changed to see if making the pipe significantly rougher or smoother would change the depth, but there was no significant difference. This suggests that the error is due to flow control. The geometry of the model matches with the geometry of the plans, so the error is likely that the plans do not match what has been built. As depths are slightly higher throughout the network, it indicates the mistake is towards the WWTP, in old pipes, rather than in the newly built network.

3.2.6 Modelling particle transport

A key concern for network operators as regards the input of additional food waste disposer derived particles is the risk of persistent in-sewer deposits, which may cause additional flood risk and have the potential for creating odours. The results of the hydrodynamic model are combined with the physical particle data measured earlier to assess the risk of deposition within the case study network. The methodology developed would also be applicable to other networks for which a calibrated network model exists.

The concept is to examine the mode of transport of the food waste disposer particles that have the highest fall velocity and so would be the most difficult to suspended and require the higher bed shear stresses to entrain. The method follows the concept originally developed by CIRIA for self-cleansing sewers (Ackers, et al., 1996), in that there should be at least a single period in every 24-hour period in which the sediment is mobile so that persistent deposits cannot form at a location.

Equation 11 Shear velocity; u = shear velocity (m/s), R = hydraulic radius (m), S = slope, g = gravity (9.81 m/s²)*

$$u* = \sqrt{RSg}$$

The network model provided depth values for all pipes at 2 minute intervals which were used to calculate the hydraulic radius which in turn is used to calculate the shear velocity (u*). The dry weather flow pattern had two peaks, one in the morning (9-10am) and one in the early evening (6.30-8.30pm), the values of shear velocity in each peak were similar. The evening peak was examined to check for the self-cleansing behaviour as regards the food waste disposer derived particles.

Table 9 The eight locations with the lowest shear velocity values at 6pm, 7pm and 8pm

6pm		7pm		8pm	
Pipe ID	Shear Velocity (m/s)	Pipe ID	Shear Velocity (m/s)	Pipe ID	Shear Velocity (m/s)
F3.1	0.021	F3.1	0.021	F3.1	0.021
F4.1	0.021	F4.1	0.022	F4.1	0.022
F5.1	0.021	F5.1	0.022	F5.1	0.022
F6.1	0.022	F6.1	0.023	F6.1	0.023
F7.1	0.022	F7.1	0.024	F7.1	0.023
F22.1	0.022	F22.1	0.026	F22.1	0.025
F13.1	0.026	F8.1	0.027	F8.1	0.027
F14.1	0.026	F148.1	0.027	F148.1	0.027

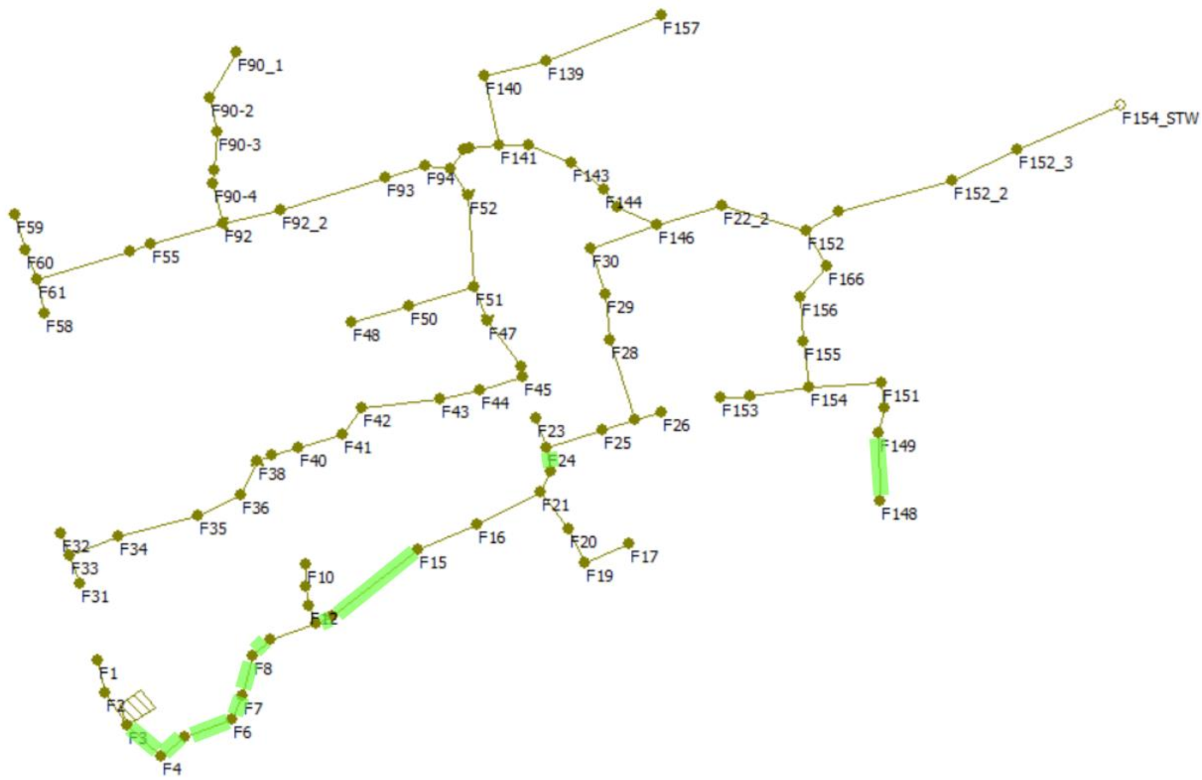

Figure 23 A pipe network schematic highlighting the areas with lowest shear for 6pm, 7pm and 8pm hydraulic conditions in green

The shear velocity pattern shown in the pipe network schematic (Figure 23) shows a pattern in which the lowest shear velocities are in pipes at the edge of the network, apart from F22.1, highlighted in green next to the F24 label on the map, which is further downstream than the other identified pipes. For a modern designed network this is expected, as the flows, depths and shear velocities are expected to increase in a downstream direction if adequate values of pipe slope are maintained. The use of a hydrodynamic model means that this method can be applied to older networks, in which the pipe slope values may result in the locations of the low shear velocity values occurring within pipes in the core of the network rather than at the edges.

To understand the transport of particles in a network it is necessary to first identify what transport mode a particle is in: suspension, saltation, bedload or has the particle settled. This can be examined under a range of different flow conditions and the following subdivision is used, where *w* = fall velocity of sediment (m/s) and u* = shear velocity (m/s). The ratios of *w* to *u** (Equation 12) are able to identify different transport modes, (Bre*users, H. & Raudkivi, A., 1991).* Identifying the different transport modes allows for locations where deposition could occur to be identified. This model has assumed food particles to behave in a non-cohesive, uniform manner.

$$\frac{w}{u*} > 6 \ settling$$

$$6 > \frac{w}{u*} > 2 \quad bed\ load$$

$$2 > \frac{w}{u*} > 0.7 \quad saltation$$

$$0.7 > \frac{w}{u*} > 0 \quad suspension$$

Equation 12 Parameters for classifying whether a particle will be in suspension, saltation, bedload or be settling

Once the mode of transport of the particle in a pipe has been determined the risk of the formation of persistent deposits can be stated. Whether errors in depth change the mode of transport depends if the modelled depths alter shear enough to change the classification a particle falls in as described in Equation 12.

This process allows for every particle size of every food measured in Chapter 2 to be assessed for deposition. The sewer conditions were chosen to reflect both the times of high daily flows and also the typical times FWDs are used is most commonly in the evening, based on a survey of Upper Rissington residents (Nichols, et al., 2020), so the times 6pm, 7pm and 8pm were chosen.

3.3 Results & Discussion

3.3.1 Mode of particle transport

For pipe F3.1 (manhole F3 > F4), a 29.6m length, 150mm diameter pipe with a slope of 0.00669m/m, was identified as a risk pipe for settlement during the selected times of 6pm, 7pm and 8pm. The only food type identified to settle during these times was eggshell and only two fractions of eggshell were identified to be at risk; 2.83cm (-1.5Φ) and 1.41cm (-0.5Φ) which represents 38.3% by weight of the total eggshell distribution, with 1.41cm being the modal fraction size for this food type. Both these fractions of eggshell particle have settling velocities of 0.128 m/s.

During the evening peak flow period (6-8pm), the values of w/u^* indicated that all particles almost every particle fraction of every type of food would remain in suspension, saltation or bedload and would not settle. The results suggest that the smaller, less dense particles move in suspension but that the larger denser particles are in saltation or bed load. It can be quite clearly seen that particles with a higher settling velocity, have a much greater proportion of particles in the bed load or saltation and fewer in suspension. This segregates particles from point of entry and suggests that residence time in sewers may vary dependent on the characteristics of the particles.

As the concept is that sewers will self-clean during peak flows, the depth profile for pipe F3.1 was used from the model to identify the time at which the depth was at its peak, 6:32pm with a depth of 0.011m, which meant that there was still a shear velocity of 0.021 m/s and the w/u^* value at this time was still just over the threshold value of 6 as it was 6.05 for both fractions of eggshell particle, thus indicating that the particles would settle. Pipe F3.1 is a pipe toward the edge of the network and is the first pipe at the edge of the network with a property attached to it, with just 1 property attached. According to the information provided by Albion Water, which agrees with the original site plans, there was supposed to be business units placed upstream of pipe F3.1 which suggests that the sewer was designed for a greater flow than which it is currently operating at. With a greater flow, it is likely that the w/u* value would be below the threshold value of 6 for settlement and the particles identified would move instead as bedload. Thus, this pipe is likely to have small deposits of food particles, only one house upstream). In combined networks, a pipe at this level of risk during DWF, with the *w/u** so close to the threshold, should be cleaned if there are a large number of contributing households upstream, in order to ensure hydraulic capacity during rainfall events.

Potential errors in the model can influence findings; whilst the total volume and velocities match well for the model, the depths are higher than expected.

To determine what mode of transport food by weight that food would be in, a UK food mix was used as a reference and all the identifiable foods that were common to the food mix and the measured particle list were used (Table 10). This meant that some measured particles taken from other countries food mix lists (Kim, et al., 2015) or chosen as they could be of interest are not accounted for in the UK mix so these are presented separately. Measured particles represent 55.219% of the UK food mix (WRAP, 2009) by weight.

Table 10 The percentage by weight, based on the UK food mix (WRAP, 2009), of each food measured for settling velocity

List of measured foods for settling velocities	Mean Particle Size (mm)	Range of settling Velocities (m/s)	Percentage of the UK food mix
Apple	2.39	0.012-0.026	5.3
Beef	2.11	0.011-0.053	*
Broccoli Stem	1.92	0.004-0.024	0.8
Cabbage	2.48	0.004-0.016	1.7
Carrot	1.8	0.005-0.027	2.4
Celery stem	0.82	0.005-0.017	*
Cheese	1.9	0.011-0.074	0.8
Chicken Carcass	2.03	0.009-0.051	5.9
Cornflakes	0.96	0.006-0.047	1.5
Egg Shells	1.53	0.028-0.128	1.5
Orange peel	2.42	0.006-0.036	2.6
Pasta	2.7	0.014-0.077	0.8
Pineapple	2.53	0.005-0.032	*
Potato	1.89	0.011-0.034	16.7
Rice	2.01	0.008-0.069	1.3
Sunflower Seeds	1.92	0.001-0.051	*
White Bread	0.58	0.005-0.040	13.2
Whole Mackerel	0.83	0.015-0.050	0.8
		Total %:	55.2

Of the foods measured for settling velocity in Chapter 2 that are also in the UK Food mix (WRAP, 2009), if we look at the highest risk pipe F3 at 6pm then by weight; 7.34% of the measured food will be in suspension, 38.98% is in saltation, 8.67% is in bedload and 0.61% may deposit, which is the eggshell. These values are derived using the information in Table 10 which identifies how much of each type of measured food accounts for in the UK food mix by weight and Equation 12 which identifies the mode of transport of particles, which using particle data from Chapter 2 identifies the proportional modes of transport for each individual food.

Table 11 A summary of pipe characteristics examined

	Pipe F3 6pm Shear 0.021m/s	Pipe F46 7pm Shear 0.049m/s	Pipe F97 7pm Shear 0.185m/s
Pipe slope (-)	0.00669	0.01311	0.108967
Pipe diameter (m)	0.15	0.15	0.225
Flow depth (m)	0.011	0.019	0.032

In Table 11, there is a summary of the pipe characteristics based on pipes chosen for their low values of shear velocities. Pipe F3 has been identified based on it having the lowest peak shear velocity and thus the greatest risk for particle deposition. F46 possesses a mean-average shear velocity value during the hours identified when FWDs are most likely to be used so this pipe is representing the “average” pipe in the network. Pipe F97 has been identified as having the highest shear velocity value for the times identified as when FWDs are most likely to be used so represents the pipe that has the lowest risk of deposition in the network.

Table 12 Proportion of the UK Food mix (WRAP, 2009), by weight, in each mode of transport in pipes of a minimum, average and maximum shear velocity

Mode of transport	Pipe ID and Shear					
	Pipe F3 6pm Shear 0.021m/s		Pipe F46 7pm Shear 0.049m/s		Pipe F97 7pm Shear 0.185m/s	
	% by weight of foods measured	% by weight of total mix	% by weight of foods measured	% by weight of total mix	% by weight of foods measured	% by weight of total mix
Suspension	13.0	7.2	50.6	27.9	97.4	53.8
Saltation	70.3	38.8	46.7	25.8	2.6	1.4
Bedload	15.7	8.6	2.8	1.5	0.0	0.0
Settling	1.1	0.6	0.0	0.0	0.0	0.0

In Table 12, it can be seen that of the whole food mix, only 0.6% by weight is expected to settle in our high risk pipe, F3. In no other pipe is any persistent deposition expected. The only particles expected to deposit are the previously described eggshell particles. As foods deemed risky, such as eggshells, were tested over less risky, more populous foods, such as vegetables, this is likely to be a conservative estimate for the proportions of foods in non-suspension modes of transport. For vegetables, only 56% by weight of the vegetables in the UK were measured and vegetables account for 38% of the total mix and they appear to be a class of foods where the settling velocity is not high. These results show that even in F3 the level of deposition will be negligible.

Table 13 The different modes of transport for foods that are not common to the UK food mix (WRAP, 2009)

		Pipe ID and Shear		
Food Type	Mode of transport	Pipe F3 6pm Shear 0.021m/s	Pipe F46 7pm Shear 0.049m/s	Pipe F97 7pm Shear 0.185m/s
Beef	Suspension	10.1	19.9	100
	Saltation	71.3	80.1	0
	Bedload	18.6	0	0
	Settling	0	0	0
Celery stem	Suspension	94.0	100	100
	Saltation	6.0	0	0
	Bedload	0	0	0
	Settling	0	0	0
Pineapple	Suspension	10.3	45.8	100
	Saltation	89.7	54.2	0
	Bedload	0	0	0
	Settling	0	0	0
Sunflower seeds	Suspension	10.3	20.2	100
	Saltation	60.7	79.8	0
	Bedload	29.1	0	0
	Settling	0	0	0

The 4 foods that were not common with the UK food mix (WRAP, 2009) that were modelled for deposition in the network and the results for the 3 pipes identified in Table 11 are presented in Table 13. This shows that none of these foods are at risk of deposition, even in the high risk pipe F3 and that in this pipe the bulk transport occurs in saltation for beef, pineapple and sunflower seeds, and the bulk is in suspension for celery stem.

The effect of error in the model must also be considered. It has been identified that the depth in the model is higher than what was measured, so the effect of the change in depth on the outcome of the mode of transport is presented in Table 14. This shows that whilst the depth does change the shear velocity values, it does not change them enough to change the mode of transport for the example of the most at risk particle, eggshell with a settling velocity of 0.128m/s. Although a slight change in the $\frac{w}{u*}$ value could result in a different mode of transport being predicted if the $\frac{w}{u*}$ was close to a threshold, the bulk of particles are not predicted to be in bedload and of the bedload particles at 6pm, only eggshell has $\frac{w}{u*}$ values above 3.5 and the majority of bedload values for the other foods lies between 2 and 3. The threshold for particles to be predicted to settle is 6. The $\frac{w}{u*}$ values for bedload particles for eggshell range from 2 to 6, but the values where $\frac{w}{u*}$ tends to 6 are pipes which already have risk of settlement, but have been identified to re-entrain during high flow, which suggests that the model could be underestimating the volume of eggshell settling in at risk pipes, but would still be identifying the same pipes as "at risk". However, when considering the data available to compare modelled and measured, this suggests that risk of settlement will not be significantly affected for most foods. However, the amount of food distributed between suspension, saltation and bedload could be affected for foods with particles on the threshold between categories, which would in turn affect the bulk average time of predicted transport, shifting it to take slightly longer, however it is unlikely to create significant change. Due to this, the model is fit for the purpose of the study.

Table 14 Comparing the effect of measured and modelled depth upon the predicted mode of transport for the most at risk particle; eggshell with a settling velocity of 0.128m/s

	Modelled				Measured			
Pipe ID	**Depth at 6pm (m)**	**Shear at 6pm (m/s)**	$\frac{w}{u^*}$	**Mode of Transport at 6pm**	**Depth at 6pm (m)**	**Shear at 6pm (m/s)**	$\frac{w}{u^*}$	**Mode of Transport at 6pm (m)**
Pipe F29>F30	0.02	0.060	2.1	Bedload	0.02	0.062	2.1	Bedload
Pipe F93>F94	0.03	0.038	3.4	Bedload	0.02	0.032	4.0	Bedload
Pipe F95>F96	0.04	0.039	3.3	Bedload	0.02	0.026	4.9	Bedload
Pipe F152_3>F154	0.04	0.080	1.6	Bedload	0.02	0.064	2.0	Bedload

3.3.2 In-field validation

To validate the flow measurements and the modelling predictions, it is necessary to do some tests in the field. This means that observations are collected to check that the predicted hydraulics match the real-life hydraulics in a specific, set number of locations. The hydraulics are tested by doing dye tests, using Flexseal tracing drain dye for drain and sewer pipes in the colour blue (Product code:DTD200_BLUE), this means that the flow velocity can be measured from one manhole to the adjacent downstream manhole by measuring the amount of time the die takes to appear at the downstream manhole. Manhole locations are identified by selecting manholes on each branch of the network which were at locations approved by the water utility. A specific requirement is that none of the main roads in the village company blocked for the purpose of the experiment, therefore manholes chosen have to be on side roads/closes with the presence of experiments will not be disruptive. These have a range of characteristics (Table 15) and were done in 3 locations, F155, F142 and F29 on the network map (Figure 24).

Table 15 Characteristics of manholes and pipes chosen for field validations

	F142 > F143	F29 > F30	F155 > F156
Pipe Diameter (mm)	225	150	150
Pipe Slope (m/m)	0.0054	0.0317	0.0067
Pipe Length (m)	29.87	31.53	28.31

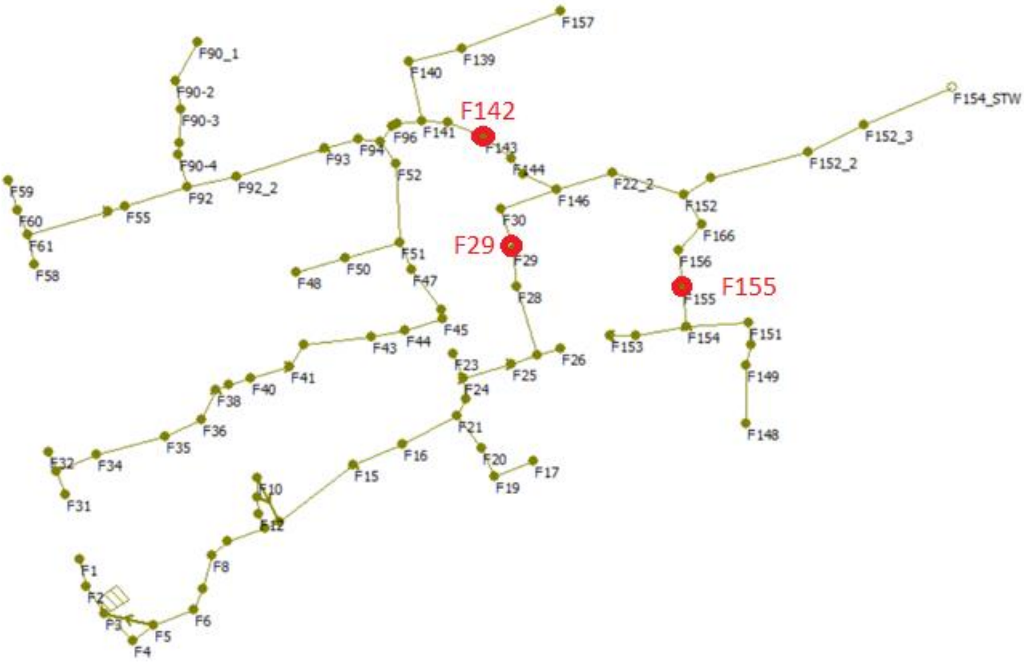

Figure 24 A map of the Upper Rissington Sewer network with manholes F142, F29 and F155 highlighted

The time of test were noted for the field measurements so that they can be checked to see how closely conditions correspond with the model predictions and all tests were carried out on a midweek day. There had been no rainfall, as previously defined, so DWF was expected. The aim was to check that the velocities were as expected based on previous measurements and modelling predictions. This was done with dye tests. Food particles (FWD processed carrot and eggshell particles) were also added to the sewer to test if they behaved as anticipated.

Dye tests are conducted by having one person adding a sample of the upstream manhole and another person at the downstream manhole with a video camera (Gopro Hero 3). Video camera is on a pole so it can be rested across the manhole so will be minimal movement of the camera, this means the camera is always at road level down into the mantle. The measurements were made by videoing the downstream manhole and the time taken for the items to get from the upstream manhole to the downstream manhole were noted. The sewer grade dye was tipped into the sewer from ground level. As all of the tests were videoed, it is possible to take accurate start and end times for each test to determine the total transport time of the dye. As the distance is known it is possible to us time and distance to calculate the velocity of the dye using Equation 13.

Equation 13 Velocity, t=time (s); d = distance (length of the sewer pipe) (m); v = velocity (m/s)

$$v = \frac{d}{t}$$

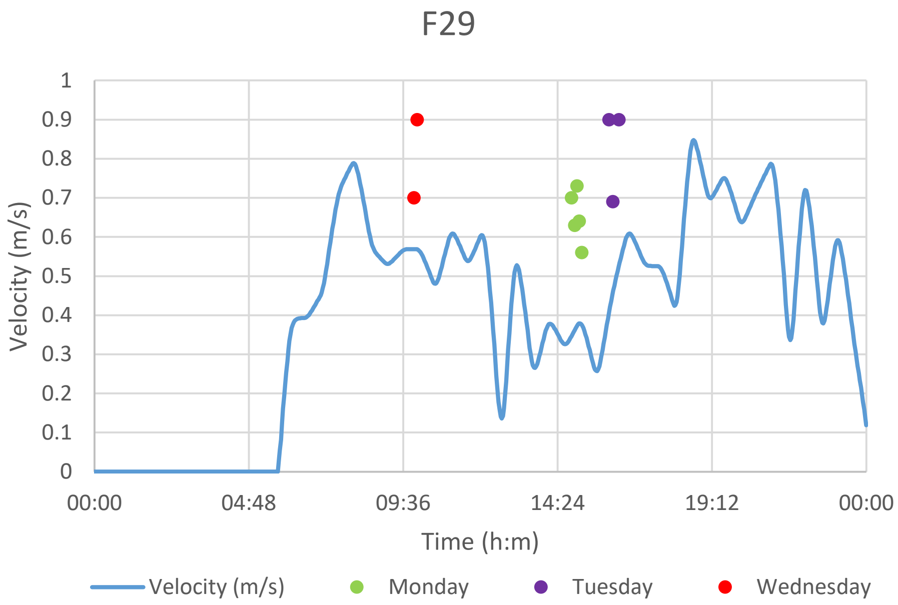

Figure 25 In-sewer dye tests for location F29 plotted as datapoints (Monday in green; Tuesday in purple; Wednesday in red) against the modelled velocity (blue)

For pipe F29 (Figure 25), the dye tests give results that are consistently higher velocities than the modelled velocity. Although the dye measurements are not taken at the same time, they are taken over a short period of time and the change in velocity over this time for each day is 0.17m/s on Monday (green), 0.21m/s on Tuesday (purple) and 0.2m/s on Wednesday (red) at this location.

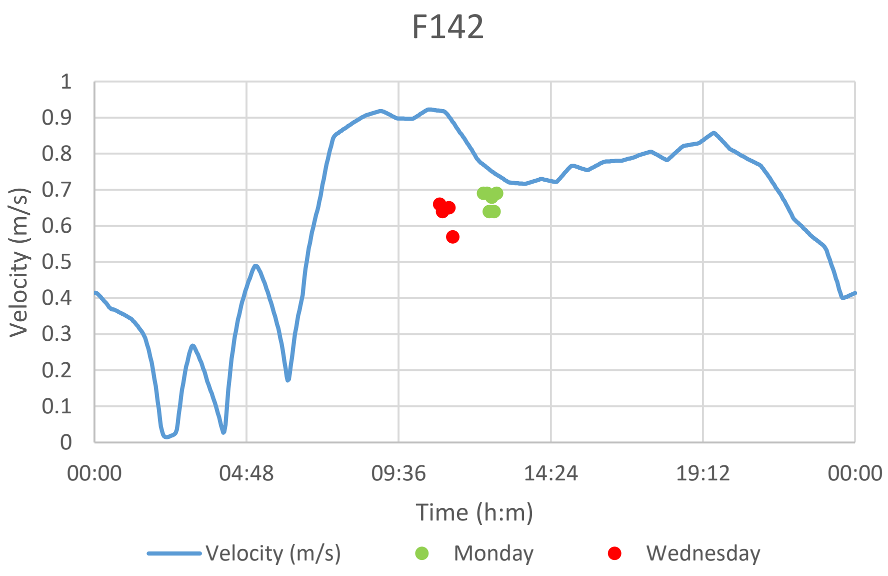

Figure 26 In-sewer dye tests for location F142 plotted as datapoints (Monday in green; Wednesday in red) against the modelled velocity (blue)

For pipe F142 (Figure 26), the dye tests give lower velocities than the modelled velocities with the difference between the maximum and minimum velocity during the measurement window on each day being 0.05m/s on the Monday (green) and 0.09m/s on Wednesday (red).

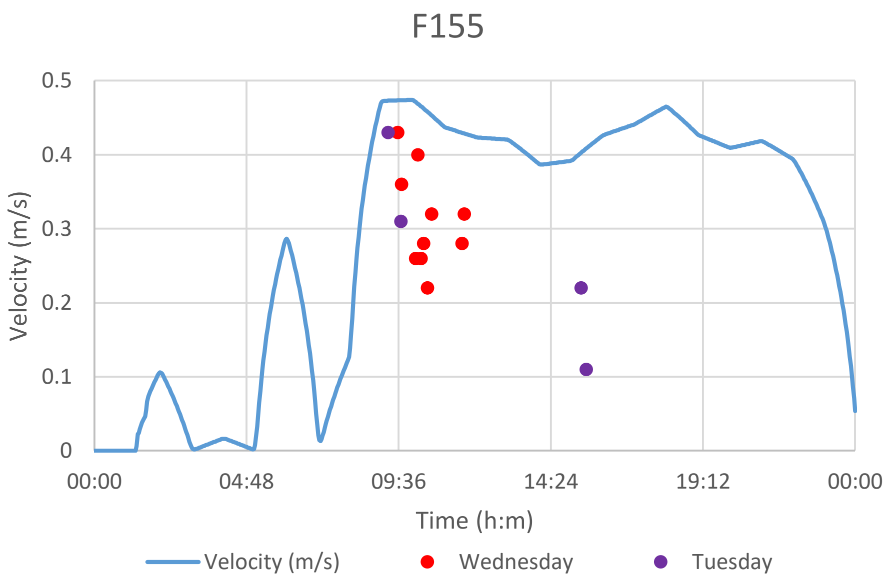

Figure 27 In-sewer dye tests for location F155 plotted as datapoints (Tuesday in purple; Wednesday in red) against the modelled velocity (blue)

For pipe F155 (Figure 27) the dye test results are lower than the modelled results. Due to the wider spread of times and number of dye tests, it is possible to suggest that the model's "box" like diurnal velocity profile at this location should have a more pronounced dip in the middle of the day based on the pattern shown by the dye tests. The difference between the dye velocity values on the Wednesday (red) is 0.18m/s, however the dye tests on the Tuesday(purple) were done during two different windows, with the morning window after 09:15 the difference being 0.12m/s and the afternoon window having a difference of 0.11m/s. As the morning window on Tuesday is at a similar time to the window measured on the Wednesday, it is possible to see that the values taken over these 2 days agree with each other.

Two foods were chosen for testing for transportation in the sewer: eggshell and carrot. Whole FWD samples were used for these tests, rather than separate fractions – this means that there is the whole particle size distribution in the sample. Each sample was 500g and the 500g was put through the FWD, separated from the water using a 3.5 Φ sieve and then put in a zip-lock storage bag. The food samples were processed in Sheffield, UK, and stored in a powered transportation fridge box and/or fridge on the Sunday before being used in the tests on the Monday in Upper Rissington, UK. When adding the sample to the sewer, the sample was tipped out of the bag as a total sample and aimed at the centre of the sewer pipe (i.e. the pipe where the water is at its deepest). Whether the sample moved during the test was observed. Food tests were observed using the same procedure and equipment (Gopro Hero 3) as the dye tests, this allowed for the videos to be reviewed, however the tests were also timed by a stopwatch and observations noted on the day.

Table 16 In-sewer observations of particle transport

Pipe	Food Type	Time	Day	Dye Test Velocity (m/s)	Observation
F155	Carrot	11:00	Wednesday	0.32	Sample moved with the flow (suspension)
F155	Carrot	11:05	Wednesday	0.32	Sample moved with the flow (suspension)
F155	Carrot	11:10	Wednesday	0.32	Sample moved with the flow (suspension)
F155	Carrot	11:34	Wednesday	0.28	Sample moved with the flow (suspension)
F142	Carrot	12:26	Monday	0.69	Sample moved with the flow (suspension)
F142	Carrot	12:29	Monday	0.68	Sample moved with the flow (suspension)
F142	Carrot	12:34	Monday	0.64	Sample moved with the flow (suspension)
F142	Carrot	12:38	Monday	0.64	Sample moved with the flow (suspension)
F142	Carrot	12:42	Monday	0.69	Sample moved with the flow (suspension)
F29	Carrot	14:53	Monday	0.7	Sample moved with the flow (suspension)
F29	Carrot	14:57	Monday	0.63	Sample moved with the flow (suspension)
F29	Carrot	15:02	Monday	0.73	Sample moved with the flow (suspension)
F29	Carrot	15:06	Monday	0.64	Sample moved with the flow (suspension)
F29	Carrot	15:11	Monday	0.56	Sample moved with the flow (suspension)
F155	Eggshell	13:27	Tuesday	0.37	Sample deposited in-pipe (settled) however showed slow movement (saltation). Returned at 09:33 (dye test velocity 0.43 m/s) on Wednesday and no sample remained.
F155	Eggshell	09:33	Wednesday	0.43	Sample deposited in-pipe (settled) however showed slow movement (saltation). Returned at 17:14 (dye test velocity 0.11 m/s) and no sample remained
F29	Eggshell	16:04	Tuesday	0.9	Sample moved with the flow (suspension)
F29	Eggshell	16:09	Tuesday	0.69	Sample moved with the flow (suspension)
F29	Eggshell	16:20	Tuesday	0.9	Most of the sample moved with the flow (saltation/bedload), however a part of the sample settled in a pipe defect in the upstream manhole. This had moved on completely by 17:18 (no dye test)
F29	Eggshell	09:59	Wednesday	0.7	Sample moved with the flow (suspension)
F142	Eggshell	10:55	Wednesday	0.65	Sample moved with the flow (suspension)
F142	Eggshell	11:06	Wednesday	0.65	Sample moved with the flow (suspension)
F142	Eggshell	11:13	Wednesday	0.61	Sample moved with the flow (suspension)

The results from the food tests show that most of the food samples were in suspension during the normal functioning of the sewer. Where the bulk-sample of eggshell during the tests had settled there was also evidence of the particles leaving the bulk-sample in the pipe and these particles appeared to be in the saltation mode of transport. The deposits were cleared during the normal in-sewer flows. The dye tests can be used to measure in-sewer velocities at the time of the food tests as there was always a dye test immediately before and after a food test. The size of the samples for the eggshell are much larger, 500g, than what would normally be added to the sewer as eggshell normally makes up only 0.012g per gram of food waste based on the UK food waste mix (WRAP, 2009).

3.4 Conclusions

A method has been developed which estimates the mode of transport of particles using shear velocity estimation and food particle fall velocity that can be applied to any network, including older networks. One of the characteristics of the Upper Rissington network, with it being new, is that the low slope and low shear zones tend to be at the outskirts of the network as opposed to the core, however it is possible for older networks to have these characteristics may occur within the core of the network. In the Upper Rissington network, one pipe, F3.1, has been identified as having a risk of deposition and for 38.3% by weight of the total eggshell distribution, representing 0.6% of the UK food mix (WRAP, 2009) has been shown to be at risk of forming a persistent deposit. In a scenario such as this where the flow is DWF and in a separate sewer, the advice would be that the one property upstream of the pipe be told to not put egg shells into the sewer.

For all other pipes, even if a particle is deposited, it will be removed during the peak dry weather flow as part of the self-cleaning sewer design. However, as summarised, 98.9% of particles, by weight, are expected to be transported without risk of deposition, even in the identified “risk” pipe, F3.1. In all other pipes, no deposits are expected to form. For the mean average shear conditions in the network during the identified period of FWD usage, which is for the “average pipe” in this network, no food particles are expected to settle, with for the 50.6% of the particles measured being in suspension, 46.7% being in saltation, 2.8% being in bedload and 0% settling. The field observations of transport mode in a small number of pipes aligned with the predicted transport mode for both carrots and crushed eggshells. This supported the view that this method could be applied more widely. It is important now to consider the biological transformations that can occur while the food particles are in transit from the household to the WwTP.

4 Quantifying the rate of in-sewer transformations of food waste particles

Chapter Overview

This chapter aims to put the organic matter content of the food waste into context of the transformation processes that naturally happens during transport in sewer networks. For this purpose, COD values of the characterised foods were measured and found to be in the range of 63-1695 mg/g COD being measured for different individual foods with the average value from the foods measured being 414 mg/g. To determine a rate of transformation of food within the sewer, a modified BOD test was undertaken using potato, which has a COD of 231 mg/g, and an oxygen consumption rate of 2.87±1.45 mg O_2 per g of potato per 24h. From these experiments it is possible to make conclusions that whilst food waste has a high COD, there does not seem to be significant oxygen use in-sewer.

4.1 Introduction

Food Waste being added to the sewer via food waste disposers (FWDs) for transport to wastewater treatment plants (WwTPs) is a method of processing domestic food waste. To maximise resource recovery at the WwTP, the ideal scenario would be zero degradation of food waste particles during transport in the sewer. Life cycle analysis (LCA) studies (Levis, et al., 2010) (Levis & Barlaz, 2011) look at food waste treatment and identifies that there is a growing need to divert food waste from landfill and that AD and aerobic composting could be potential solutions. Reducing domestic food waste has been modelled have a positive impact upon the environment without significant negative macroeconomic impact, with -0.1 to -0.5% impact on GDP in the EU identified from reducing demand for agri-food production and jobs (Philippidis, et al., 2019), however there is still need for household food waste management. FWDs have the potential to make this resource easily utilizable by facilitating the transport of food waste through sewer networks from individual properties to the WwTP, which are good opportunities for installing equipment for recovery of energy and nutrient resources, with little added energy for transport (Iacovidou, et al., 2012).

However, there are problems associated with additional organic matter as degradation of existing organic matter in sewer consumes oxygen. The organic matter transformation processes in sewers are described by the WATS model (Hvitved-Jacobsen, et al., 2002) (Hvitved-Jacobsen, et al., 2013) and this shows both aerobic and anaerobic processes. The organic matter in sewers can be separated into either readily biodegradable substrate, readily hydrolysable substrate, slowly hydrolysable substrate and biomass. Under aerobic conditions, the readily biodegradable organic matter is converted into biomass during aerobic heterotrophic respiration. There is also fast hydrolysable and slow hydrolysable substrate which via hydrolysis (in either aerobic or anaerobic conditions) can be transformed into fermentation substrate, which can then be readily biodegraded under anaerobic conditions to form biomass. In an ordinary well-functioning sewer pipe operating as a gravity sewer, aerobic conditions are normally achieved as the supply of oxygen from the sewer atmosphere exceeded the amount of oxygen that are used by the heterotrophic microorganisms in the wastewater.

Anaerobic conditions typically occur in rising mains where the full flowing pipes means that no oxygen is transferred from a sewer atmosphere to the wastewater. Anaerobic conditions can also occur in gravity sewers with low slope where the air-water mass transfer is reduced or in systems with unusual high loads of readily biodegradable organic matter. Aerobic conditions are favourable in sewers compared to anaerobic conditions as anaerobic processes can result in undesirable odours and corrosion of the sewer pipe from bi-products of anaerobic respiration. For the purpose of this study, only aerobic conditions are being examined.

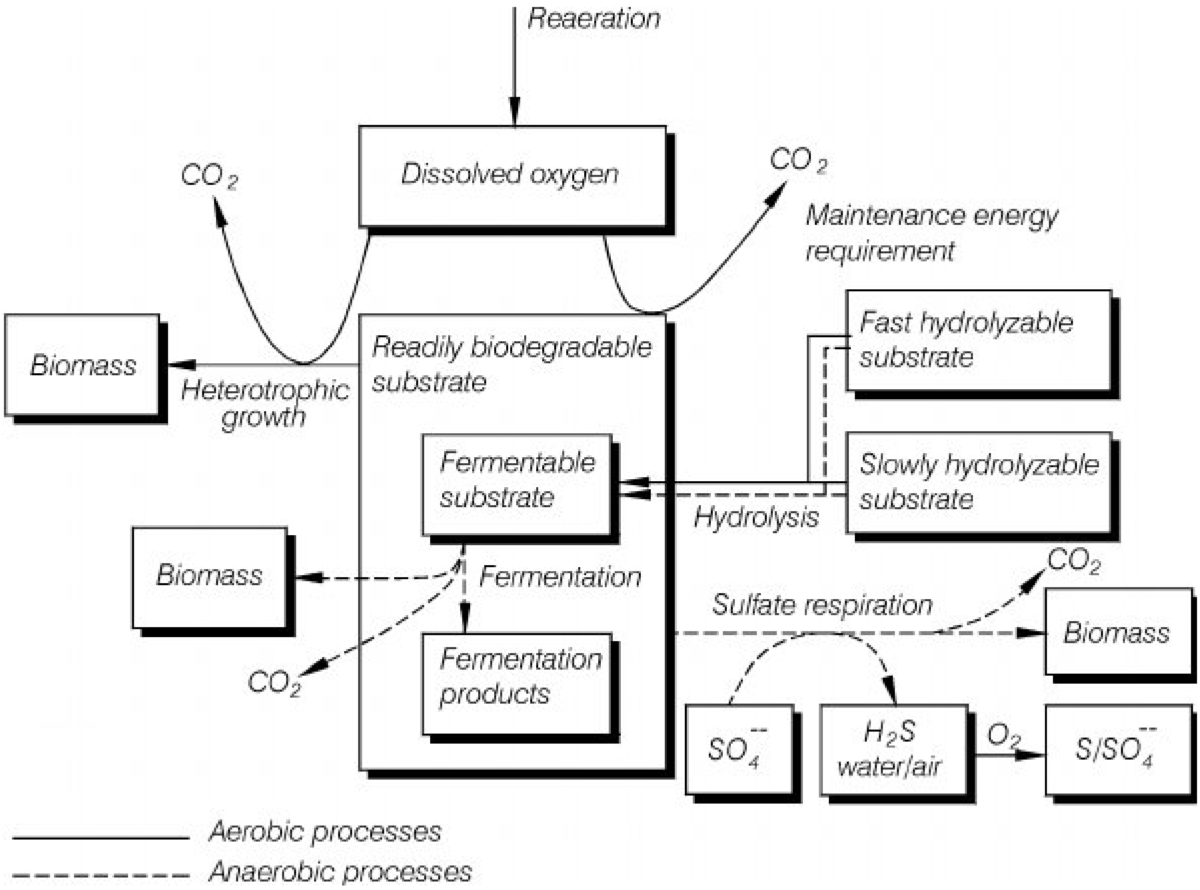

Figure 28 An integrated aerobic and anaerobic concept for transformations of wastewater organic matter and sulphur in sewer networks (Hvitved-Jacobsen, et al., 2002)

A potential concern with adding food waste to the sewer network would be that if it does have a high rate of degradation in the sewer, which means that it has an oxygen demand, this could lead to in-sewer oxygen depletion and the creation of anaerobic conditions which can lead to corrosion and odour problems. As seen in Figure 28, anaerobic processes create hydrogen sulphide (H_2S), which is the main sewer-gas. H_2S has a strong odour, like rotten eggs, and also can be transformed to sulphuric acid (H_2SO_4) which can corrode concrete and metal, reducing the lifespan of sewer assets. For these reasons, sewers are designed with the aim of being aerobic.

In order to achieve this, it is necessary to consider if the added organic material from the food waste would cause any problems in the sewer network and how much is likely to reach the wastewater treatment works. To evaluate this problem, it is mainly necessary to assess the bioavailability of the organic matter in the food waste as this is both what would contribute to energy production in the form of methane at the wastewater treatment works as well as potentially causing problems in the sewer networks.

The potential benefit of using FWDs is that studies have shown that the use of FWDs increases the methane production at WwTPs (Moñino, et al., 2017) (Evans, et al., 2010). This has been reported as being increased methane production of up to 190% in a pilot-plant set-up where the feedstock mimicked 80% of homes having FWDs installed and also an increase in methane production of 57-136% where the feedstock used was at 40% using anaerobic membrane technology (Moñino, et al., 2017) and 46% more biogas at Surahammar in Sweden than before FWD where there was 50% of homes having FWDs installed using mesophilic anaerobic digestion (Evans, et al., 2010).

To this end, the goal would be to get as much organic matter to the treatment works as possible to be available for AD and have little loss of organic matter in the sewer due to in-sewer processes converting the organic matter in the food waste into CO_2 through heterotrophic metabolism activity.

To know how much organic matter gets to the WwTP, the amount of food waste degradation in sewer must be quantified. The organic matter quality of the food waste may change during the sewer transport due to heterotrophic activity of the microbial communities in sewers, however, in order to determine if this is the case, the bioavailability of the organic matter needs to be understood and there is little evidence regarding the bio-availability of the food waste in the sewer and how travel and retention time affects this. Determining the organic matter quality of the food waste with respect to bioavailability and transformation rates will help predict the remaining available organic resource that can be recovered in energy at the wastewater treatment plant.

One of the parameters available to evaluate organic content and bioavailability is via oxygen demand, specifically using the Chemical Oxygen Demand (COD) test and Biochemical Oxygen Demand (BOD) test. Both tests indirectly quantify the organic matter in the samples by measuring the amount of oxygen used to oxidise the organic matter in the sample. This is an important water quality indicator and way to quantify the amount of organic matter in water.

For COD, it measures how much of a strong chemical oxidant is needed to oxidise all organic materials in the sample, whereas BOD can determine the oxygen consumption by microbes during a defined period, hence providing information about the bioavailability of the organic matter in the sample. In the COD analysis a strong chemical oxidant is used to oxidise all the organic material in the sample to carbon dioxide and water (complete oxidation). There information available on the COD of a food waste mix (Kim, et al., 2015), but no data from individual foods. Here they measured that the COD_{tot} of their food waste mix was 3.4±1.1mg/l per gram of food waste. What is important to know from a utility perspective is the amount of COD within food waste so that the anticipated load on the WwTP is known and whether it has the capacity for additional COD. In DWF sewage in the UK under aerobic conditions, the estimated removal of COD_{tot} is 6% in a 7.2km gravity sewer with an average retention time of 1.5h (Almeida, 1999).

BOD is generally measured by determining how much oxygen is used for the degradation of the organic matter over a certain period of time. As sewers generally have short hydraulic residence times, it is appropriate to measure BOD over short periods of time to represent this. Based on evidence from the sewer process model, 24 hours has been taken as a good period, capturing the degradation of both readily biodegradable substrate and readily hydrolysable substrate (Hvitved-Jacobsen, et al., 2013) comparing the COD of the food to the BOD measured over 24 hours will therefore allow the determination of which proportion of the organic matter from the food waste is bioavailable and therefore possible to mineralise to CO_2 under aerobic sewer transport conditions.

To achieve maximum flexibility for applying data around the world, the approach in this project has involved determining total COD values of individual foods based on the list of foods that have been investigated for particle size distribution in Chapter 2. This allow calculation of COD of food mixes of different composition. Therefore, using the rate at which food waste is transformed in sewers, to be determined using a 1-day sequential BOD test (1DS-BOD), it is then possible for this information to be used in a model to determine how much organic matter is used by in-sewer microbial processes.

Temperature of sewage can also affect the rate at which microbial processes occur in sewage. Within a certain range, the warmer the environment, the faster the microbes can metabolise, however, high and low temperature extremes can denature the enzymes used to metabolise and this prevents growth. What temperature range bacteria can grow in depends on its classification. Water leaving domestic properties is on average 25°C (Frijns, et al., 2013) and the sewer environment is between 10 to 25 °C with a yearly average of 17.5 °C in the UK (UK, 2022). For this type of environment, you would expect to find mesophilic microorganisms.

4.2 Materials & Methods

4.2.1 COD of food

Food samples were prepared by being homogenised in a food blender for a minimum of 5 minutes. Homogenised samples were used in lieu of fractionated samples that had been through the FWD as to get an accurate COD of the material the concentration must be consistent and this would not be possible with a FWD processed sample as the particles are all different sizes which can grossly affect concentration in small samples. There is also a limit to the size of particle that can easily be pipetted, so the smaller the particles are, the easier they are to handle for the experiment, which overall means more accurate COD values with homogenised samples.

The foods used in the COD tests Table 17 were the same as those tested in Chapter 2, which characterises the physical properties of the particles from food waste disposers, and were prepared in the same way as described in Chapter 2. The list of foods was chosen based on foods which were in the US (Kim, et al., 2015) and UK food mixes (WRAP, 2009), with a focus on foods which were anticipated to have higher settling velocities such as eggshells (Mattsson, et al., 2014) and food waste such as chicken carcass.

Table 17 List of food types where the COD is measured, grouped according to the UK food mix (WRAP, 2009)

Food Group	Food type
Bakery	White bread
Dairy/Eggs	Cheese Egg shell
Fruit	Apple Orange peel Pineapple
Meat/Fish	Beef Chicken Whole mackerel
Staples	Cornflakes Pasta Rice Sunflower seeds
Vegetable	Broccoli stem Cabbage Carrot Celery Potato

4.2.1.1 Overview of COD procedure

To measure COD, the sample is mixed with a strong chemical oxidant which will oxidise all the organic matter in the sample (Baird, et al., 2017). In these measurements the sample was mixed with potassium dichromate in a sulphuric acid solution. The potassium dichromate is a strong oxidising agent in the presence of an acidic environment and completely oxidises the organic matter which results in a colour change of the liquid due to the formation of Cr^{3+}. The colour change corresponds to the amount of oxidation which has occurred and thus is an indirect measure of much organic matter was in the sample. The colour change is measured using spectroscopy, so measures the absorbance of the sample, which allows for quantification of the colour change by comparing the colour to a blank.

The COD kits used are Hach Lange 0-1000 mg/L O_2 cuvette tube tests, which means they are suitable for detecting COD within the range of 0 to 1000 mg/L.

Before a tube can be used, the sediment was re-suspended by inverting the tube a few times.

A standard curve of known COD values was created using alpha-glucose so that absorbance can be translated into a COD value. As the complete oxidation of organic compounds produces carbon dioxide and water, it is possible to theoretically calculate the COD. The theoretical COD reaction for glucose is:

Equation 14 Formula for cellular respiration

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6H_2O$$

The COD value represents the grams of oxygen used divided by the grams of substrate used and in this case the substrate is glucose.

Equation 15 Calculation of the COD of a gram of glucose

$$\frac{(6\ x\ 32) gram\ of\ oxygen}{(6\ x\ 12) +\ 12\ +\ (6\ \times\ 6) gram\ of glucose} =\ 1.067\ g\ COD\ per\ gram\ of\ glucose$$

This means that different solutions of known COD can be made up and the absorbance measured to create a standard curve which is then used to convert the absorbance of samples of unknown COD into COD measurements. A stock solution of glucose was made and this was diluted to make the glucose concentrations used to create the curve. The concentrations (COD mg/L) measured were: 0, 125, 250, 500 and 1000 using a stock solution and serial dilution. Each concentration was measured using 4 different samples, with each single measurement value given by the machine being determined by measuring the sample 10 times at a slightly different incidence of the light. The blank used to zero the spectrophotometer was the equivalent of 0 COD mg/L as it used water. This is then plotted Figure 29 to get an equation for the trend-line and this had an $R^2\ =\ 0.9968$ showing that the regression fits very closely with the data.

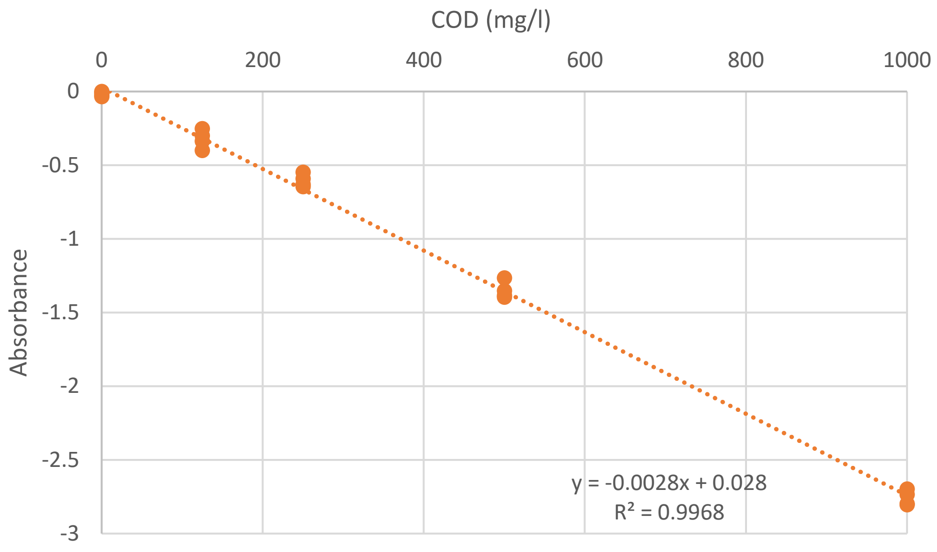

Figure 29 Absorbance calibration curve using glucose dilutions of known COD values

The equation of the trend-line ($y = mx + c$) for the measured absorbance of glucose concentrations of known COD was:

Equation 16 Calibration equation for converting absorbance to COD in the format y = mx + c

$$Absorbance\ Value = -0.0028\ COD\ Value + 0.028$$

Which can be rearranged to convert absorbance readings into COD values using:

Equation 17 Calibration equation for converting absorbance to COD with COD value as the subject

$$COD\ Value = \frac{Absorbance\ Value - 0.028}{-0.0028}$$

This is the equation used to convert the absorbance readings of the food COD tests into COD values.

2.0ml of homogenised food sample was pipetted into the cuvette tube and the lid thoroughly closed before inverting the tube to mix the sample with the reagent. For the blank, COD-free water was used. The procedure used a hot-block which was pre-heated to 148°C and the cuvette tubes were heated at this temperature for 2h. After this, the tubes were removed and left to cool to 60°C before once again being inverted to mix the solution. The tubes were then left to reach room temperature (20°C) so that they could be wiped clean and the absorbance at 600nm measured of the solution in the Hach Lange DR 3900 spectrophotometer. Absorbance of the samples was measured using the blank to zero the spectrophotometer. The absorbance readings were converted into COD values using a standard curve of known COD values.

4.2.1.2 Preparation of food sample for COD

The food waste sample was prepared as a suspension of blended food waste in tap water and initially 5g/l of food was used, however, the mass of foods was lowered accordingly to obtain measurements which were within the range at which the COD test can accurately measure as the upper detection limit is 1000 mg/L. The sample was then added to 1L of tap water and blended using a Kenwood BL370 kitchen food blender until the sample is fully blended into a homogeneous solution, this should be for at least 5 minutes. A 15ml sample is taken from the 1L the blended solution whilst is was well mixed and 2 further samples are created by doing two 50% serial dilutions. For example, this means that if the original 1L sample was a 5g/L concentration, the dilutions would be at 2.5 g/L and 1.25 g/L. A full list of concentrations used is shown here:

Table 18 A table of the final 3 concentrations of food used when measuring COD

Concentrations of food used for COD test (g/L)				
5 2.5 1.25	2 1 0.5	1.25 0.625 0.3125	1 0.5 0.25	0.5 0.25 0.125
Apple Broccoli Cabbage Carrot Celery Chicken Breast Eggshells Orange Peel Pineapple Skin Potato Rice	Beef Mackerel Pasta	Bread	Cheese Cornflakes	Sunflower seed

Three different concentrations of food are measured to ensure that the values derived for the COD of the food is within the range of the test and are plotted to ensure that there is a linear correlation as which is expected. If there is not a linear correlation this suggests that the concentrations are at or over the limit of the 1000mg COD vials and the process is repeated using lower initial concentrations of the food until a linear correlation is obtained. For the purpose of the experiment, an R^2 of less than 0.95 is used[3] to decide to repeat the test using a lower concentration of foods. Once there is a linear correlation, this suggests that the concentrations are within range. The food test is then repeated at this concentration, resulting in 6 plot points per food (Figure 30). An example is shown here for carrot:

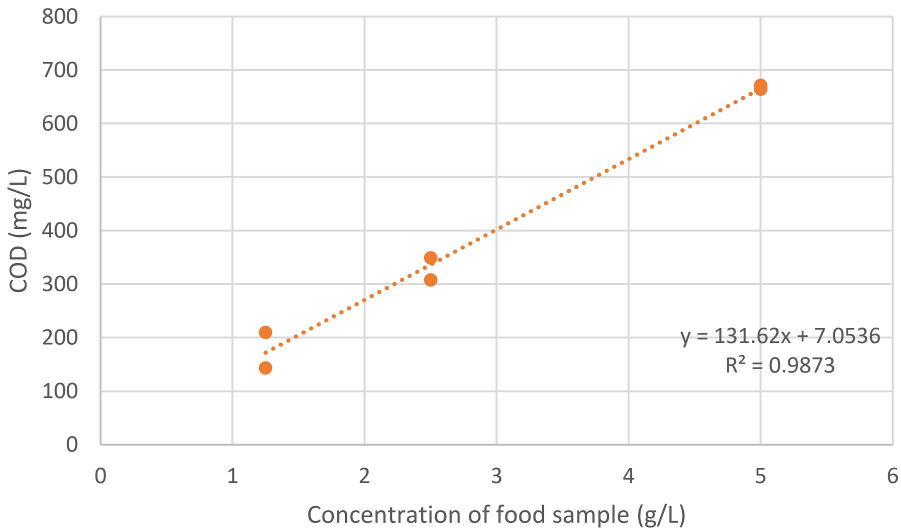

Figure 30 An example, using carrot, of the relationship between food concentration and COD

The equation of the line for the 6 plots is used to determine the relationship between g/L of the food and absorbance. The equation of the fitted straight line is used to calculate a value for absorbance per gram of food. The equation from the standard

[3] For all foods apart from eggshell, the R^2 value of 0.95 was used as the defining factor. For eggshell, the high settling velocity of the shell particulates made it very difficult to maintain a homogeneous suspension to add to the COD vials. This limitation in the experiment when working with eggshell resulted in the eggshell R^2 of 0.80 due to the difficulty in handling the sample.

curve of glucose is then used to convert the absorbance per gram into a COD (mg/l) for a gram of food in 1L. For carrot this is 139 ±18 mg/L of COD per gram of food[4].

4.2.2 One Day Sequential BOD Test

In order to determine the proportion of COD that is bioavailable in wastewater, within typical sewer transport times, a one-day sequential BOD (1DS-BOD) is used. This is an experiment undertaken over 2 days and is used to identify how much of the organic matter from food waste was biologically oxidised BOD. It uses 30 bottles per run with 27 bottles being experimental bottles and 3 bottles being used as a quality control for the cleanliness of the bottles and the diluent.

The experiment itself is carried out over two days and in the absence of light to remove any effect of photosynthetic organisms as they are active in-light and could produce oxygen which would mean that the oxygen levels measured would be a combination of the oxygen being produced by any photosynthetic organisms present in the wastewater and the consumption of oxygen by respiring organisms (Baird, et al., 2017). Oxygen production is not wanted during the experiment, as what is being measured is oxygen reduction and this is caused by respiring organisms using oxygen whilst consuming organic matter. The absence of light was achieved by using a temperature controlled water bath which was impenetrable to light and a foil blanket covering to prevent any light from getting in and also to act as an insulator from any drafts.

The incubation bottles were glass 250ml stoppered BOD bottles (VWR International LTD) which were used in a thermostatically controlled water bath under standard conditions at 20°C +-1°C capable of holding 30 BOD bottles. The dissolved oxygen (DO) Probe (membrane electrode: WhiteBoxLabs laboratory grade DO probe) was calibrated by measuring the voltage across the membrane at 1 known levels of DO. The first measure was 0% oxygen which was achieved using a solution of sodium sulphite, which chemically removes the dissolved oxygen from solution. 100% oxygen saturation was also measured using water that had been fully aerated using

[4] The equation in Figure 30 doesn't go through zero as the equation is only being used within the range of measured values, therefore the value in the text isn't the equation, but the outcome of using the equation to calculate the mg/L of COD

an aeration stone. The probe is cleaned in-between measurements by rinsing with tap water and was checked for calibration on each day that the probe was used and if the calibration check was incorrect then the probe was serviced, given a fresh membrane, new electrolyte and recalibrated. The sewage was sourced from a domestic WwTP that serves the south of Sheffield, UK. Real sewage is needed as this is the source of the microorganism community that lives in the sewage. The sewage sample is then used as a starting inoculant for the BOD experiment. A starting inoculant is a small sample of microorganisms that is introduced into a suitable situation for growth, in this case, the substrate the microorganisms work upon is the food waste added to the experiment.

The sewage was collected from the sewage treatment works after the sewage had been through Coarse and Fine screening as well as grit removal, which means that it has had large debris removed, such as wetwipes. The sewage is collected in 500ml bottles and stored in a 2°C fridge and was normally used within 2 days and never used beyond 5 days. Sewage collections were done on a Tuesday between the hours of 10am and 11am. Each experimental run, of which there are 3 in total, took place on a different week, which meant that as the sewage was collected fresh for each experimental run, the sewage was from a different sampling run each time and not from the same date then stored for subsequent experiments. The COD of the sewage was measured immediately before the start of the experiment, not on the day the sample was taken, so that the COD for the experiment was known. For each run, 4 samples of well mixed sewage were taken and the COD measured with the average measurement presented in Table 19.

Table 19 Summary of COD of the inoculant (sewage)

	COD of Starting Inoculant (mg/L)
Run 1	283.3 +/- 35.7
Run 2	283.5 +/- 8.0
Run 3	401.7 +/- 51.2

The diluent is made according to the standards described in Standard Methods (Baird, et al., 2017) for making diluent for BOD tests. The diluent is used as a quality control for the BOD test to show that the diluent itself does not cause oxygen depletion the levels of oxygen depletion are measured for 3 bottles in each run of the experiment. The quality controls do not have any sewage added nor do they have any food samples added, they contain only the diluent water and this is done to determine if there were any contaminants in the diluent. It also shows that the glassware is clean. The quality control is otherwise subject to the same conditions as the other bottles in each run of the experiment.

The food sample used for the experiment was potato and this was prepared by 200g of potato being put through the FWD. The sample was taken from the whole particle size distribution and was not separated into fractions, but the water was drained from the sample using a 3.5Φ sieve and well-mixed before a sample was taken, so as to be representative of the particle size distribution of the particles from the FWD. Potato was chosen as it is a common food type and has an unremarkable particle size distribution and settling velocity profile (Chapter 2), it has also been modelled in the sewer (Chapter 3).

The experiment tests 9 conditions (Table 20) and each condition has 3 replicates within the experiment meaning that there are 27 experimental BOD bottles and the remaining 3 bottles are used as quality controls for the diluent.

Table 20 Description of each experimental condition measured in the 1DS-BOD test. Each condition had 3 repeats in each experimental run (i.e. there were 3 bottles with those conditions, resulting in 27 experimental bottles.

Experimental Condition	Concentration of sewage (Volume %)	Total mass of potato sample (g)
1	1%	0g (control)
2	2%	0g (control)
3	3%	0g (control)
4	1%	1g Potato
5	2%	1g Potato
6	3%	1g Potato
7	1%	2g Potato
8	2%	2g Potato
9	3%	2g Potato

The experiment run-time is approximately 48h, with DO measurements being made at the start of the experiment (0hrs), after the first 24h before the food sample is added (24hrs) and at the end of the experiment (48hrs).

At the start of the experiment the experimental BOD bottles are prepared with either 1%, 2% or 3% sewage, each being diluted with the diluent water. The diluent water is poured slowly to ensure that it is well aerated during pouring to ensure a high starting DO, which is sufficient to ensure that the level of dissolved oxygen is above 80% saturation. The microorganisms from the sewage feed on the small amount of organic content in the diluted sewage, consuming oxygen in the process, and a rate of oxygen consumption can be calculated by measuring the DO at 0hrs and 24hrs. By measuring the change in percentage DO between 24hrs and 48hrs allows for a rate of oxygen consumption to be calculated, which can then be compared to the experimental control (sewage but no additional food).

To convert percentage dissolved oxygen to dissolved oxygen saturation concentration in bulk water phase it is possible to use the equation for the solubility of oxygen (Equation 18). Conditions in the experiment had a temperature of 20°C, an actual air pressure of 1 atmosphere (760 mm Hg) and a saturated vapour pressure of 17.5 mm Hg. This equation tells you what 100% dissolved oxygen equals in mg/l in the conditions described. To convert the percentage DO results, the S_{os} value is multiplied by the percentage DO value to get what that the oxygen concentration is in mg/L (eg. 85% DO would be the S_{os} multiplied by 0.85, which in the described conditions would give a value of 5.5mg/l).

Equation 18 Equation for the solubility of oxygen. S_{OS} = dissolved oxygen saturation concentration in bulk water phase (in equilibrium with the atmosphere) (g O_2 m^{-3}); P = actual air pressure (mm Hg); p_s =saturated pressure at temperature T (mm Hg); T = temperature (°C) (Hvitved-Jacobsen, et al., 2013)

$$S_{os} = \frac{P - p_s}{760 - p_s}(14.652 - 041022T + 0.00799T^2 - 0.0000777T^3)$$

4.3 Results & Discussion

4.3.1 COD of food Results

The COD (mg/g) of foods (Table 21) has been measured with values ranging from 1695mg/g for sunflower seeds to 63mg/g for celery and the mean average COD being 435mg/g. For most foods the standard error of the estimate (SEE) the mean average being ±33mg/g between ±1mg/g and ±50 mg/g however there are 4 foods with higher values; beef ±51mg/g, rice ±68mg/g, eggshells ±70mg/g and orange peel ±90mg/g. When comparing the SEE to the COD per gram of food as a percentage, there is a mean average percentage SEE of 14.6%. Eggshell shows the highest percentage SEE of ±60.3% and also identifies pineapple skin and celery, which both have low COD values, as having a high percentage SEE of ±32.2% and ±22.2% respectively where the next highest percentage of the foods with a SEE below 50mg/g is carrot with a ±12.9%. Beef, which has a SEE of over ±50mg/g, has a low % SEE of ±9.8%. Variation is higher in foods usually where it was difficult to maintain a well-mixed homogeneous solution, such as egg shell.

Table 21 List of COD values for each food

Food	COD per gram of food (mg/g)	Standard error of the estimate (± mg/g)	Percentage standard error of the estimate (± %)
Sunflower Seeds	1695	24	1.4
Cornflakes	1030	24	2.3
Bread	790	38	4.8
Cheese	659	24	3.6
Pasta	578	20	3.5
Beef	519	51	9.8
Chicken Breast	437	47	10.8
Mackerel	415	15	3.6
Orange Peel	343	90	26.2
Apple	259	24	9.3
Potato	231	1	0.4
Broccoli	183	19	10.4
Rice	179	68	38.0
Carrot	139	18	12.9
Pineapple Skin	118	38	32.2
Eggshells	116	70	60.3
Cabbage	79	9	11.4
Celery	63	14	22.2
Mean	435	33	14.6

Since the digestible organic content of food for human consumption is measured as the food's energy content, usually in Kilocalories, it may be suggested that COD could be related to the calorific value of foods. Since calorific values are routinely measured and readily available from food packaging, quantifying this relationship could enable a simple estimation of COD. Calorific values have also been used to assess food waste as a source of producing energy (Triyono, et al., 2018) (Serbanescu, et al., 2017) (Saini, et al., 2012). Figure 31 shows the COD of all the foods, apart from eggshell as there was no literature calorific value for shell, plotted against the manufacturers calorific values presented in Table 1 of the appendix.

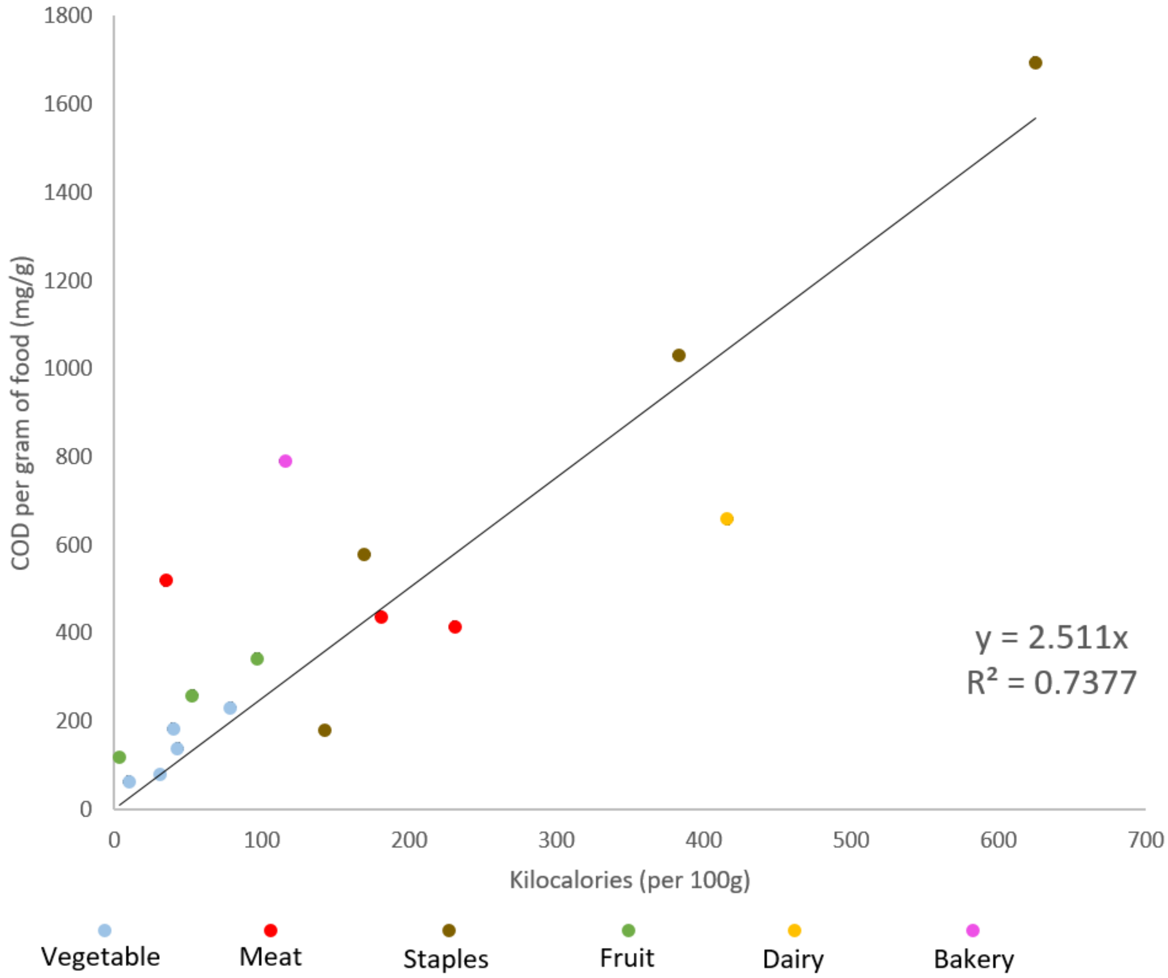

Figure 31 The relationship between COD and calorific value

As can be seen in Figure 31, there is a relationship between COD and calorific value with an R^2 of 0.74 which means that there is a good positive correlation. The variability could be from the COD experiment or it could be that the calorific values from the food packaging are not accurate. Based on the relationship given, it is possible to estimate the calorific value as shown in Equation 19.

Equation 19 The relationship between Kilocalories and COD of food

$$Kilocalories\ per\ 100gram\ of\ food = 2.511\ COD\ per\ gram\ of\ food$$

In (Kim, et al., 2015) the COD of food waste is measured as 1500 ± 470 mg/L for 440g of food suspended in 58L of water (7.59g/L) which means that the COD is 198± 62 mg/g

*Table 22 Measured and estimated values (highlighted with *) of COD of individual foods in the US foodmix from (Kim, et al., 2015)*

Food Group	**Food**	**COD per gram of food (mg/g)**	**Proportion of food used in** (Kim, et al., 2015) **(g) from a 440g total**
Meat	Beef	519	13.2
	Pork*	981.801	8.8
	Chicken	437	6.6
	Hot dog*	251.1	4.4
	Ketchup*	256.122	2.2
	Mustard*	180.792	2.2
Dairy	Milk (with cereal)*	165.726	44
	Cheese	659	8.8
	Cottage cheese*	263.655	8.8
	Butter*	1870.695	4.4
	Salad oil*	2259.9	8.8
Grains	Mac & cheese*	926.559	13.2
	Cornflakes	1030	8.8
	Cheerios*	962.55	8.8
	Rice	179	13.2
	Spaghetti with tomato sauce	578	17.6
	Bread	790	8.8
	Sugar*	4268.7	8.8
Fruits	Apple	259	13.2
	Banana skin*	225.99	22
	Cantaloupe rind*	55.242	8.8
	Pineapple skin	118	17.6
	Watermelon rind*	82.863	22
	Orange peel	343	13.2
	Grapefruit*	85.374	44
Vegetables	Broccoli	183	13.2
	Cabbage	79	26.4
	Carrot	139	8.8
	Celery	63	8.8
	Cucumber peel*	40.176	4.4
	Lettuce*	35.154	17.6
	Pepper seeds and core*	77.841	4.4
	Potato	231	24.2

The mean average COD in the artificial mix, derived from the directly measured values and values estimated using the calorie-COD curve, is 564mg/g and has a standard deviation of 842mg/g. 202.4g worth of food in the mix, which accounts for 46% of the mix by weight, uses values directly measured in the laboratory, for the remaining 237.6g (54%) the COD per g of food is estimated based on the relationship between COD and calories in Equation 19 and the calorie information in Table 2 of the Appendix. Using this information, it is possible to estimate that the mix has a COD of 420mg/g, which is higher than the literature value of 198± 62 mg/g (Kim, et al., 2015). The measured COD only accounts for 35.7% of the total COD estimated for the food mix with the remaining 64.3% of the total COD being from the values derived using the COD-calorie equation. As some of the foods being estimated using the COD-calorie equation are listed as rind/peel/core and the calorie values found are for the whole foods, it is possible that the COD values for these items have been over-estimated as the main body of the fruit/vegetable is where there is the most nutritional value so it would be expected that the skin of the food would have a lesser value. The R^2 for the COD-calorie equation was 0.74, this accounts for 74% of the variation in the values derived from the equation.

4.3.2 One Day Sequential BOD Test Results

The results of the 1DS-BOD tests showed the inclusion of food resulted in a greater oxygen demand than the absence of food and also that the by increasing the volume of food that there was also an increase in oxygen demand. This trend is exemplified in Figure 32.

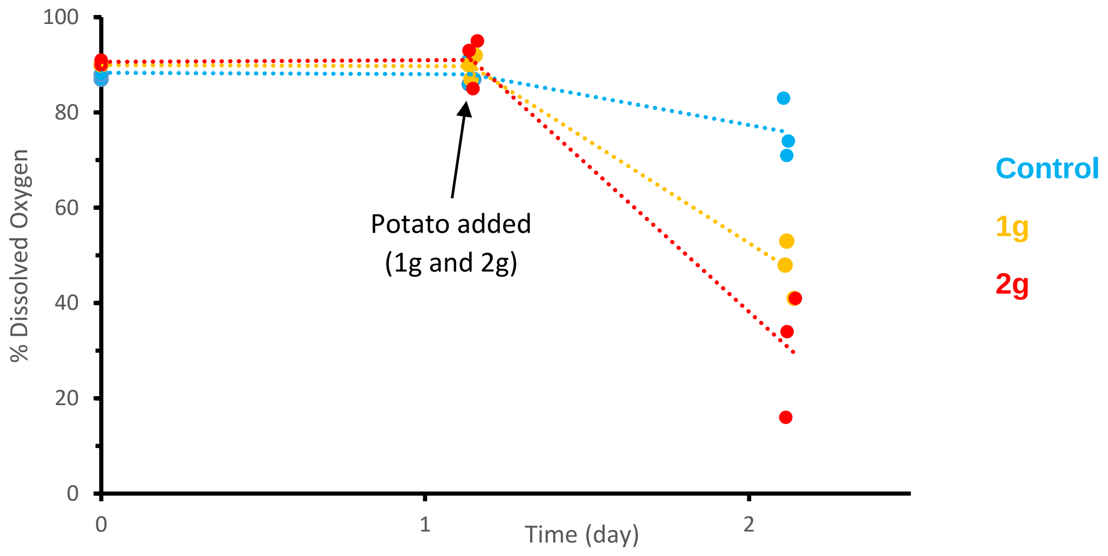

Figure 32 Example experimental data using Run 2's 1% sewage bottles

For day 2, the average oxygen consumption in each experimental run from the control is removed from the oxygen consumption from the bottles containing potato as this represents the background oxygen consumption and the contribution of the potato is what is to be quantified. Figure 33 presents the data for each run of the experiment. The data is presented to demonstrate that the percentage of sewage used does not seem to have a significant effect upon oxygen consumption as there is no pattern to the data. This also suggests that the inoculant was not a limiting factor. Using all of the data collected, the oxygen consumption rate is 2.87±1.45 mg O2 per g of potato per 24h.

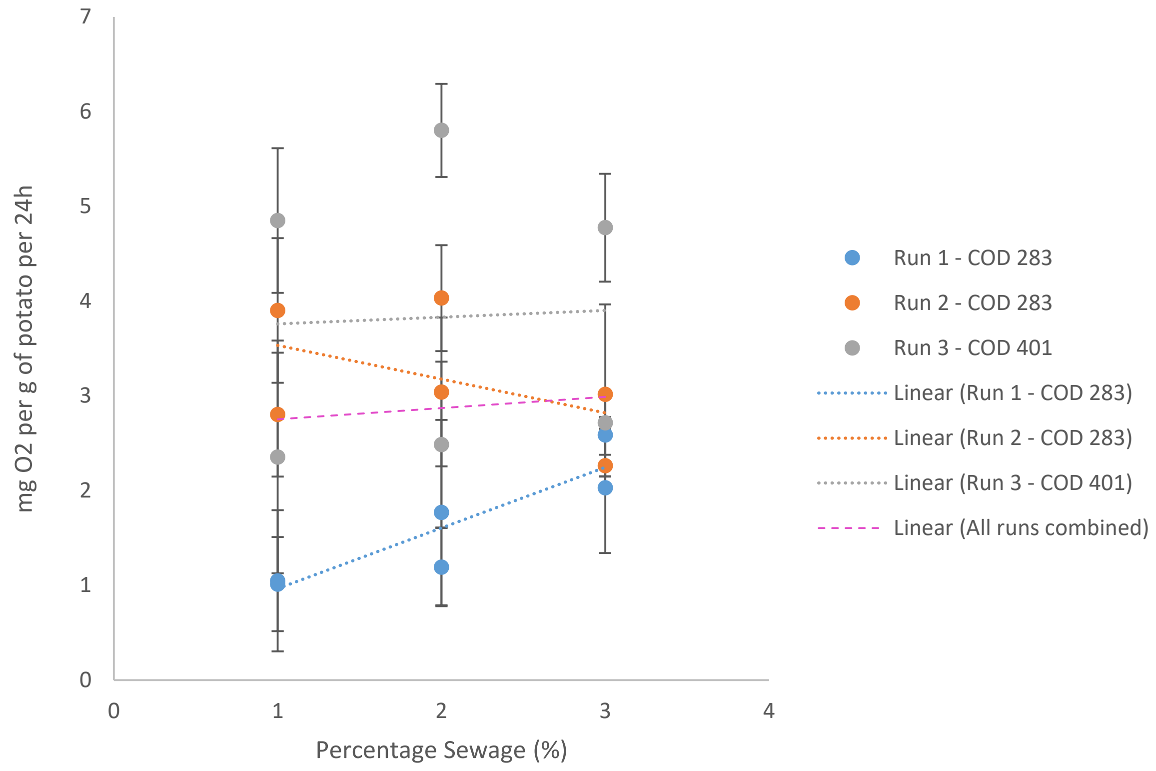

Figure 33 The oxygen consumption of each run of the experiment. The error bars represent the standard deviation from the mean.

4.3.3 Discussion

To measure the COD for the foods is a relative quick test which is why all of the foods were measured. Due to the fast settling velocity of the eggshell, it was more difficult to maintain a homogeneous solution for measuring the COD which resulted in a larger deviation in the COD results. This suggests that if there are other foods with a high settling velocity, which have not been studied in the thesis, then these could also be difficult to get COD values with low variability between results. The relationship between COD and the calorific value has a good relationship with an R^2 of 0.74 and this is despite the natural variability of organic matter. This suggests that for calculations where the COD of a food has not been measured, using the calorific value of the food and converting it using relationship in Equation 18 is realistic. This relationship was used to allow the total COD of the US food mix (Kim, et al., 2015) to be calculated so that it could be compared to the literature data. The COD of potato, which is used as the food for the 1DS-BOD is 231 mg/g.

For the results of the 1DS-BOD, the low values are hard to evaluate and this is due to the total oxygen consumption being such a small factor. This means that during the course of the experiment other variables can affect the overall results. Variables such as the sewage composition will be affecting the results as when comparing the impact of the oxygen consumption from potato, which is small, to the effect of the variability in the sewage, which is also small, the magnitudes of the two variables are similar. The oxygen consumption rate for potato is measured as 2.87±1.45 mg O_2 per g per 24h.The ratio of BOD used over the 24h compared to the total available COD is 0.012 or this can be presented as 1.2% of the COD seems to be bioavailable during sewer transport with a residence time of up to 24 hours. This means that there is very little loss of organic content in the sewer and that particles from FWDs arrive at the WwTP with negligible degradation.

The carbon footprint of using FWDs as part of integrated waste management systems has been modelled (Maalouf & El-Fadel, 2018), however, how the in-sewer processes affect this carbon footprint has not been accounted for and only the direct emissions from waste degradation during systems operation at the WwTP are accounted for and the only upstream emissions that are considered is those from materials and energy (electricity and fuel). As the rate of degradation in sewer seems to be very low, then this suggests that the carbon footprint of FWDs used by Maalouf and El-Fadel would not be significantly affected by factoring in in-sewer processes.

In future it would be useful to have more foods tested using the 1DS-BOD technique so that it can be determined if the higher COD foods have a significantly higher or lower level of oxygen consumption. Based on the COD results, the maximum COD food, Sunflower Seeds (1695 mg/g), and the minimum, Celery (63 mg/g). If there was shown to be a high rate of oxygen consumption in other foods then it would be useful to know if the rate of oxygen consumption changed over time and for this an oxygen uptake rate (OUR) reactor could be used, however, where oxygen uptake is low, this would be at the limit of detection for the experiment.

4.4 Conclusions

COD values of the characterised foods were measured and found to be in the range of 63-1695 mg/g COD being measured for different individual foods with the average value from the foods measured being 414 mg/g. It is possible to use the calorie-COD curve to gain some insight into the COD of food waste. The R2 of 0.74 shows that there is a good positive correlation, but that it is not a totally accurate conversion. This may be useful where it is not feasible to measure the COD of a food or where the accuracy of the COD value is not critical, however the direct measurement of the COD value is more accurate.

The rate of transformation of food within the sewer using the 1DS-BOD test with potato, which has a COD of 231 mg/g, was measured to be 2.87±1.45 mg O_2 per g of potato per 24h, giving a BOD:COD ratio of 0.012 for potato.

5 Is there a role for food waste disposers in the circular economy?

Chapter Overview

This chapter will take the information gathered in the previous chapters, to examine if the introduction of residential food waste disposer that link with an existing foul/combined system could be seen to follow the principles of the circular economy.

5.1 Introduction

The aim of this chapter is to examine the potential for the use of food waste disposers in the circular economy. The concept of the circular economy is based on concept of designing systems that aim to minimise waste and pollution by keeping materials in productive use for as long as possible and waste should be treated as secondary raw materials that can be recycled for re-use reducing society's impact on natural systems. This concept was originally developed for manufacturing processes but its definition has evolved to cover a broader range of systems such as energy and waste processing systems.

5.2 Methods

For this evaluation, the Upper Rissington site is used as a case study to estimate the amount of food waste, that is produced and disposed of into the sewer network, how or if the food waste is degraded during sewer transit and if following treatment at the WwTP if a useful secondary raw material could be obtained that would be considered a potential contribution to the circular economy. Thus the analysis will consider the materials in food from the point the food waste enters the sewer at the domestic property until the point at which the waste enters the wastewater treatment plant (WwTP) and can be potentially processed to release useful secondary raw materials.

5.2.1 Determining residence time in sewer

The second step is to determine the residence time of particles in sewers. In Chapter 3, a model-based framework was used to determine whether particles are in different modes of transport at different times in every pipe in the Upper Rissington network. Knowing the mode of transport; whether a particle is in suspension, saltation, bedload or settled, is key to knowing how long those particles take to move along the sewer pipe.

If the particle is in suspension, then the particle moves at the same speed as the wastewater and deposition formation is highly unlikely. The model, described in Chapter 3, has all the pipe length data and also the velocity of sewage in every pipe during a 24h period. This allows for the residence time of wastewater to be calculated (Equation 20) based on the velocity and the length of the pipe.

Equation 20 Velocity, rearranged with time as the subject; t= time (s); d = distance (length of the pipe, m); v = velocity (m/s)

$$t = \frac{d}{v}$$

However, particles which are in saltation or bedload can have their transport time determined as a proportion of the flow rate of the sewage using the approach described in (Penn, et al., 2018) where they use a generalised form (Equation 21**Error! Reference source not found.**). In this case the potential for deposit formation is possible, especially if the particles are travelling as bedload.

Equation 21 Equation for modelling gross solids transport in a sewer network where η is a dimensionless constant (described in Equation 222) v_{GS} = velocity of gross solids (m/s) ; Q = actual flow (l/s) ; v_{WW} = velocity of wastewater (m/s);

$$v_{GS} = \eta \cdot Q^{1.2} v_{WW}$$

Equation 22 Constant η in equation 21. S = longitudinal slope of the pipe; SG = specific gravity

$$\eta = 1.95 \cdot SG^{-2.5} \mathrm{S}^{0.25}$$

The specific gravity of the particle is calculated at a temperature of 25°C using the density of the wastewater of 997.07 kg/m^3. For the density of the particle, the value for eggshell is used (Table 5) which is 1165 kg/m^3. This was chosen as this is the maximum particle density.

Equation 23 Specific gravity; ρ_p = density of particle (kg/m^3); ρ_{sewage} = density of water (kg/m^3)

$$SG = \frac{\rho_p}{\rho_{sewage}}$$

If at a given time the *w/u** ratio is greater than 6, then deposit formation is expected to occur and the particle will have settled. In this scenario, as the particle does not move, the velocity would be zero during the time where the sewer conditions allowed for settlement. If the sewer network adheres to the CIRIA self-cleansing sewer concept (Ackers, et al., 1996) then the settled particles would be resuspended during the normal 24h variation in flow.

This means that depending on the mode of transport (suspension, bedload/ saltation and settling) it is possible to calculate the time of travel of a particular particle size in an individual pipe. To calculate the longest residence time in the network flow conditions at 7pm are used as this will represents a time when particles from FWDs are likely to enter the network and the property used to calculate the maximum transport time will be chosen on the basis of it being at the edge of the network and also having the longest transport time, based on a particle in suspension. This means that the property attached to F3 will be used.

5.2.2 Quantifying total degradation

In Chapter 4, the rate at which organic carbon in food waste particles in presence of wastewater was degraded was estimated in the laboratory. This information is used, combined with the residence time estimates to calculate the amount of the organic matter degraded by FWD particles being transported through the sewer system from input to entry to the WwTP.

In Chapter 4 a COD value for the US food mix (Kim, et al., 2015) was calculated to be 420mg/g and for the literature value of 198± 62 mg/g (Kim, et al., 2015) in this chapter it was calculated that the oxygen consumption rate for potato as 2.87±1.45 mg O_2 per g per 24h. For the purpose of estimating how much of the UK food mix (WRAP, 2009) is degraded in-sewer, the value for potato will be used and this is making an assumption that the rate of degradation will be the same. This means that for the total COD of the food mix there is the assumption that 1.2% of this is available BOD over a 24h period.

For one household, the estimated amount of food waste disposed via FWD by the Water Research Council (WRc, 2010) by one person is 0.1656kg per day, which based off the 2020 UK average of 2.4 people per household (UK Government Office for National Statistics, 2020), would put the average output per household at 0.397kg. There are supposed to be 150 FWDs installed at Upper Rissington so this would give a total input of 59.36kg per day to the WwTP. Which when combined with the COD per gram of food mix means that there is 163800mg COD in 0.39kg food waste and 24931200mg COD in 59.36kg food waste.

5.3 Results and Discussion

5.3.1 Degradation in sewer

Whilst this approach is simple, it is possible to apply the principle with more finesse by calculating the residence time based on mode of transport of each particle fraction of each food for each property in the network and calculating the degradation of each property's based on this customised transport time. Transport times for individual pipes are calculated using Equation 20 for determining time elapsed from distance travelled and velocity of the solid, and Equation 21 to determine the velocity of gross solids in a sewer. The transport times are calculated for each pipe at the specified time, T, then summed for each pipe involved to determine the total time. To improve the accuracy of this, then the first pipe would be calculated using conditions at time T, but the second pipe would be calculated using conditions at time T plus the amount of time it took for transport to occur in the first pipe, with this summative time shift occurring for each following pipe.

For the property attached to F3 at 7pm the particles in suspension would take 70 minutes, or 1hour 10 minutes, to reach the WwTP. When looking at the particles in saltation or suspension, which is characterised by the gross solids transport equation, the estimated transport time for the sewer conditions at 7pm is significantly longer with the estimate generated being 15.6 days. Upon closer inspection, the majority of this time was due to the very slow transport in the two pipes at the end of the network, F3 and F4, which had been identified as pipes at risk in Figure 23 in Chapter 3 which highlighted pipes with low shear velocities. From F5 onwards, gross solids transport was estimated to be 17.5 hours and of the pipes with the lowest shear velocities, only pipes F3 and F4 suggested gross solids transport times of this magnitude. Of the 242 houses modelled, only 1 household serves F3 and F4. A limitation of the current method to estimate transport time is that the hydraulic conditions remain static. A more accurate estimation would be to have hydraulic conditions changing as time passes during particle transport.

Using the 3 times identified for duration of transport, 70 minutes for suspension, 15.6 days for house F3 gross solids transport time and 17.5 hours for the next longest gross solids transport time it is possible to estimate the degradation. Using the COD value of 420mg/g and the assumption that for the total COD of the food mix there is 1.2% of this is available BOD over a 24h period, this estimates that 0.21 mg/g COD is lost per hour and the summary is presented in Table 23.

*Table 23 Summary of COD loss from the network. * Note: for times beyond 24h, degradation rates will not be valid. Estimates are presented for completeness.*

Network route and mode of transport	F3 to WwTP Suspension	F3 to WwTP Gross solids	F5 to WwTP Gross Solids
Transport Time	1.1 hour (70 minutes)	374.3 hours* (15.6 days)	17.5 hour
mg/g COD is lost	0.0006	0.1872*	0.0088
mg COD lost from 1 household (based on daily input of 0.39kg food waste)	0.21	72.99*	3.41
mg COD lost from the whole network (based on daily input of 59.36kg food waste)	32.65	11109.22*	519.40
Percent (%) mg COD lost from total COD	0.0001	0.0446*	0.0021

Levels of degradation of food waste is low in-sewer so this means that food waste COD is transported mostly intact to its destination at the WwTP, however, the estimates are only valid for times up to 24h as the experiment only ran for 24h. That the gross solids (saltation and bedload) are estimated to take days to travel through pipes F3 and F4 suggests that it would be worth doing longer experiments to ensure that these types of high risk pipes are well enough assessed.

The weakest assumption made is that all foods will have the same rate of degradation as potato and all estimates made until more degradation information is collected will be subject to the assumption that the BOD:COD ratio is the same for each food. It could be that the rate of degradation of different foods is not dissimilar to that of potato but in the absence of evidence, it is not possible to state this as anything but an assumption. It would be strongly recommended that the 1DS-BOD test be repeated with the lowest COD and the highest COD foods so that if there is a relationship between the COD per gram of food the BOD:COD ratio it will be apparent.

5.3.2 What does this mean for the circular economy?

For the Upper Rissington site, there are no processes at the WwTP that are designed to generate energy so the extra organic content that the food waste inputs to the treatment facility would go to sludge. This still contributes to the circular economy as the sludge can be used as a raw material to enrich soil.

When applied to a larger scale system, such as a city WwTP with the facility to generate biogas, it is possible for FWDs to have a greater contribution to the circular economy when compared to the Upper Rissington site. Here the additional COD from the food waste can be used to boost energy production. However, as the residence time of the food in the network is longer, the loss of COD in the network will be greater, however based on the results it will be 0.0029% for a 24h period, which means that for residence times under 24h that the assuming the total COD of the food mix would get to the WwTP would be a suitable approximation. However, the experiment only characterised up to 24h and for residence times beyond 24h further experiments to be undertaken.

5.4 Conclusions

This chapter demonstrates the method feasibility to estimate the degradation in a small network, however it also highlights that the current data is only suited to residence times up to 24h and that further experiments to characterise degradation after the 24h point would be needed.

This also highlights knowledge gaps which need to be filled if more robust estimates of degradation in the sewer is to be estimated, mainly that there is the large assumption that the BOD:COD ratio of 0.012 for potato is applicable to all of the other foods.

The key information here is that for times under 24h in a network, the level of degradation appears to be negligible and this suggests that it is an efficient way of getting food waste to AD if the WwTP has the facility and that it adheres to the circular economy principles.

6 Conclusions and Future Work

6.1 Conclusions

This research does not definitively state whether FWD should be utilised to manage food waste but instead provides preliminary insights and assessment frameworks to allow water companies to make evidence based decisions about the effects of FWDs upon their assets in different locations. The assessment process outlined in the thesis allows for water companies to assess sedimentation risk and to give estimates, taking into account food waste production and in-sewer degradation as to whether the food waste could enhance sludge or anaerobic digestion at the water treatment plant.

In Chapter 2 18 common food types, encompassing a wide range of foods, were characterised to obtaine particle size data and particle settling velocities. The modal particle size varied between 0.59mm and 4.76mm and the standard deviation varied between 0.34mm to 0.62mm. Particle size distributions are shown to conform well to Gamma distributions, meaning they can be characterised by just two parameters.

The fall velocity measured was used to estimate particle density. Most densities measured are close to water, so submerged density small and particles unlikely to deposit. Very few foods have higher density. This results in these particles being entrained into motion at low values of boundary shear stress. The ease of entrainment means that the vast majority of food types are highly unlikely to form persistent deposits in sewer pipes. Fractionwise data allows you to examine new food mixes and means the knowledge can be applied globally by modifying the proportions of particles based on the local food mix.

Egg shell particles showed a submerged density estimate considerably higher than the other food types which means that the entrainment threshold was considerably higher than for the other food types. This results in the deposition risk of egg shells being higher than for other food types. Despite the risk, the overall prevalence of egg shell in waste food is very low (around 1%) so it is unlikely to cause significant deposition issues.

In Chapter 3 a framework was developed to estimate blockage risk that can be applied to any network, including older networks. This was done for a 24h dry weather flow period as this represents a conservative flow when considering the risk of deposition. The challenge of modelling Upper Rissington is that it is difficult to simulate DWF in such a small network. This is due to flow depths being at the limit of detection for the flow monitors and also due to the small flows being at the limit of what the modelling software can model as it requires minimum flows to maintain model stability.

In the Upper Rissington network, there is deposition risk at edge of network. This is due to sewer design for new networks having low slope and low shear zones tending to be on the outskirts of the network as opposed to the core. For older networks it is possible that low slope and shear pipes may occur within the core of the network. For properly designed systems it would be expected that the blockage risk be low.

In terms of how representative Upper Rissington is compared to other catchments in the UK, it is arguably quite a flat and uncomplicated catchment. The slopes within the network range from 0.0043m/m to 0.15306m/m and there are no assets such as pumps or storage tanks within the network, meaning that there are no areas where anaerobic digestion of biomass can occur. Due to this, an extra step would be necessary to model the transport of the particles through these assets and this could affect how long the particles remain in transit for. Due to the biochemical research in chapter 4 being on aerobic processes, it would only be applicable through assets which are aerobic and also only in networks where the transit time was up to 24h, as this was the maximum run time of the study.

98.9% of particles, by weight, are expected to be transported without risk of deposition, even in the identified “risk” pipe, F3.1 which was identified to have a risk of 38.% by weight of the eggshell distribution forming a persistent deposit. In a scenario such as this where the flow is DWF and in a separate sewer, the advice would be that the one property upstream of the pipe be told to not put egg shells into the sewer. In all other pipes, no deposits are expected to form.

The field observations of transport mode in a small number of pipes aligned with the predicted transport mode for both carrots and crushed eggshells. This supported the view that this method could be applied more widely.

In Chapter 4 there was a comprehensive characterisation of the COD of foods, the generation of a value to convert calorific values into COD values and also a rate of degradation for food was measured for potato particles. COD values of the characterised foods were measured and found to be in the range of 63-1695 mg/g COD being measured for different individual foods with the average value from the foods measured being 414 mg/g. The rate of transformation of food within the sewer using the 1DS-BOD test with potato, which has a COD of 231 mg/g, was measured to be 2.87±1.45 mg O_2 per g of potato per 24h, giving a BOD:COD ratio of 0.012 for potato. There are large errors for BOD due to the low detection levels being at the limit of what can be measured.

In Chapter 5 the feasibility of estimating the degradation in a small network has been demonstrated. However, the process also highlights that the current data is only suited to residence times up to 24h and that further experiments to characterise degradation after the 24h point would be needed. This also highlights knowledge gaps which need to be filled if more robust estimates of degradation in the sewer is to be estimated, mainly that there is the large assumption that the BOD:COD ratio of 0.012 for potato is applicable to all of the other foods. The key information here is that for times under 24h in a network, the level of degradation appears to be negligible and this suggests that it is an efficient way of getting food waste to AD if the WwTP has the facility and that it adheres to the circular economy principles. When applying this concept to other regions the temperature of the experiment in Chapter 4 should be considered, as it was done at 20°C. It is to be expected that for higher temperatures that the rate will increase and that at lower temperatures that the rate will decrease.

6.2 Future Work

A database of settling velocities and particle sizes of ground food particle sizes is published, with a wide range of different foods having being assessed, and has been created in a way so that additional foods can be added to the database in future using a standard measurement protocol. The data base has been structured so that for different markets, local food mixes can be created and the overall settling behaviour of typical local food mixes can be derived. This will allow the blockage risk assessment method to be applied internationally.

The InfoWorks model of the Upper Rissington field site is modelling a new network, so may not reflect how the particles may behave in the same network 30 years in the future. It would be useful for water companies to use existing models, combined with an estimate of pipe deterioration of their networks to be able to forecast future behaviour of particles in the network, not just how particles behave in the network as it is now. In addition, the current model is small and uncomplicated. It would be useful to generate results based on cities to see if the behaviour of food waste would change significantly.

Assessing the risk posed by particles relies on the use of Shield's Equation (Equation 8), however, this formula is for spherical particles. The test with the erosion meter using eggshells, a plate-like particle, demonstrated that plate-like particles do not behave in the same way as described in shields. To get more accurate prediction of risk, it would be beneficial to do more tests on plate-like particles in an annular flume. The procedure would create a "new" Shields curve for plate-like particles and the procedure should follow the same standard protocol that was used to generate the original Shields equation for spherical particles. It would be expected that the values for the "new" Shield's curve for plate like particles would look similar to the original Shield's curve for the smaller particles as they will tend to be more spherical, but the "new" curve will more significantly diverge from shields, the bigger the plate-like particles are. This allows for a more accurate estimate of critical shear stress for the plate-like particles.

In terms of the COD of the foods in the database, this has been well characterised and follows a simple protocol which means that additional foods could be easily added. Other things which could be done is further exploring the relationship between BOD and calorific value and also determining if whether food was raw of cooked had a significant impact.

It would be useful to further investigate the rate of degradation of the particles from food waste disposers, mainly by investigating to see if the assumption that the BOD:COD ratio is the same for all foods. To do this it is possible to continue to investigate using the BOD technique or it could be more useful to look at it using an

Oxygen Uptake Rate (OUR) reactor. The BOD is that the procedure is simple, doesn't require complex equipment and the experiment is unlikely to encounter technical problems, however, the advantage of using OUR is, that if it works, the data quality and resolution is of a much higher quality and will much better reflect the in-sewer conditions as the degradation of particles will not be linear. The BOD values give the average rate over 24h, whereas the OUR would be anticipated to give multiple rate readings over each hour of the 24h period and these rates would be expected to create a rate curve. If looking at periods of over 24h, OUR would be advantageous as it does not allow the experiment to run anaerobically, whereas there is a risk of the oxygen running out in BOD. Despite the higher resolution data in OUR, for times under 24h it is possible to still get useful degradation using BOD.

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Appendix

Table 1 - Calorific values and sources of food information used in Figure 31

Kcal per 100g	Brand name of food item	Reference
53	Tesco Pink Lady Apple	https://www.tesco.com/groceries/en-GB/products/284477450
132	Tesco sliced beef	https://www.tesco.com/groceries/en-GB/products/299957880
40	Tesco loose broccoli	https://www.tesco.com/groceries/en-GB/products/257231200
31	Tesco Sweet Heart Cabbage	https://www.tesco.com/groceries/en-GB/products/254941983
43	Tesco Fresh & Easy Carrot Batons	https://www.tesco.com/groceries/en-GB/products/264871629
10	Nightingale Farms Celery	https://www.tesco.com/groceries/en-GB/products/292214122
416	Cathedral City Mature Cheddar	https://www.tesco.com/groceries/en-GB/products/277925449
181	Tesco Whole Roast Chicken	https://www.tesco.com/groceries/en-GB/products/290315714
387	Cornflakes	https://www.tesco.com/groceries/en-GB/products/254843379
97	Orange peel	https://www.calorieking.com/us/en/foods/f/calories-in-fresh-fruits-orange-peel-zest-rind-raw/rwuDId7tRPCUzjVySnkPQw)
170	Tesco Penne Twinpack	https://www.tesco.com/groceries/en-GB/products/299912707
3.5	Pineapple Skin	https://www.myfitnesspal.com/food/calories/pineapple-skin-640311671
79	Maris Piper	https://www.eatthismuch.com/food/nutrition/maris-piper-potatoes,141074/
143	Tilda Pure Steamed Basmati Rice Classic	https://www.tesco.com/groceries/en-GB/products/262311847
625	Tesco Sunflower Seeds	https://www.tesco.com/groceries/en-GB/products/256515195
116	Warburtons Toastie Sliced White Bread	https://www.tesco.com/groceries/en-GB/products/254942348
231	Whole mackerel	https://www.yazio.com/en/foods/mackerel-cooked.html

Table 2 - Calorific values and sources of food information (Tesco, 2021) used in Table 22

Kcal per 100g	Brand Name of food item	Reference
391	Tesco pork loin	https://www.tesco.com/groceries/en-GB/products/258261577
100	Herta Classic Frankfurters Hot Dogs	https://www.tesco.com/groceries/en-GB/products/254273333
102	Heinz Tomato Ketchup	https://www.tesco.com/groceries/en-GB/products/254722768
72	French's America Classic Yellow Mustard	https://www.tesco.com/groceries/en-GB/products/256363765
66	Tesco Whole Milk	https://www.tesco.com/groceries/en-GB/products/254656399
105	Tesco Natural Cottage Cheese	https://www.tesco.com/groceries/en-GB/products/274436278
745	Tesco British Salted Block Butter	https://www.tesco.com/groceries/en-GB/products/290920510
900	Tesco Extra Virgin Olive Oil	https://www.tesco.com/groceries/en-GB/products/254516076
369	Homepride All American Classic Mac & Cheese	https://www.tesco.com/groceries/en-GB/products/301392610
383	Cheerios Multigrain Cereal	https://www.tesco.com/groceries/en-GB/products/308488819
1700	Silver Spoon Granulated Sugar	https://www.tesco.com/groceries/en-GB/products/252528422
90	Bananas Loose	https://www.tesco.com/groceries/en-GB/products/275280804
22	Cantaloupe Melon Each Class 1	https://www.tesco.com/groceries/en-GB/products/256582085
33	Tesco Watermelon	https://www.tesco.com/groceries/en-GB/products/254638605
34	Red Grapefruit	https://www.tesco.com/groceries/en-GB/products/253561443
16	Tesco Cucumber	https://www.tesco.com/groceries/en-GB/products/253558972
14	Tesco Little Gem Lettuce	https://www.tesco.com/groceries/en-GB/products/253560041
31	Tesco Sweet Peppers	https://www.tesco.com/groceries/en-GB/products/295673143