Impact of kitchen waste grinder application with water conservation strategies on urban water sewerage systems

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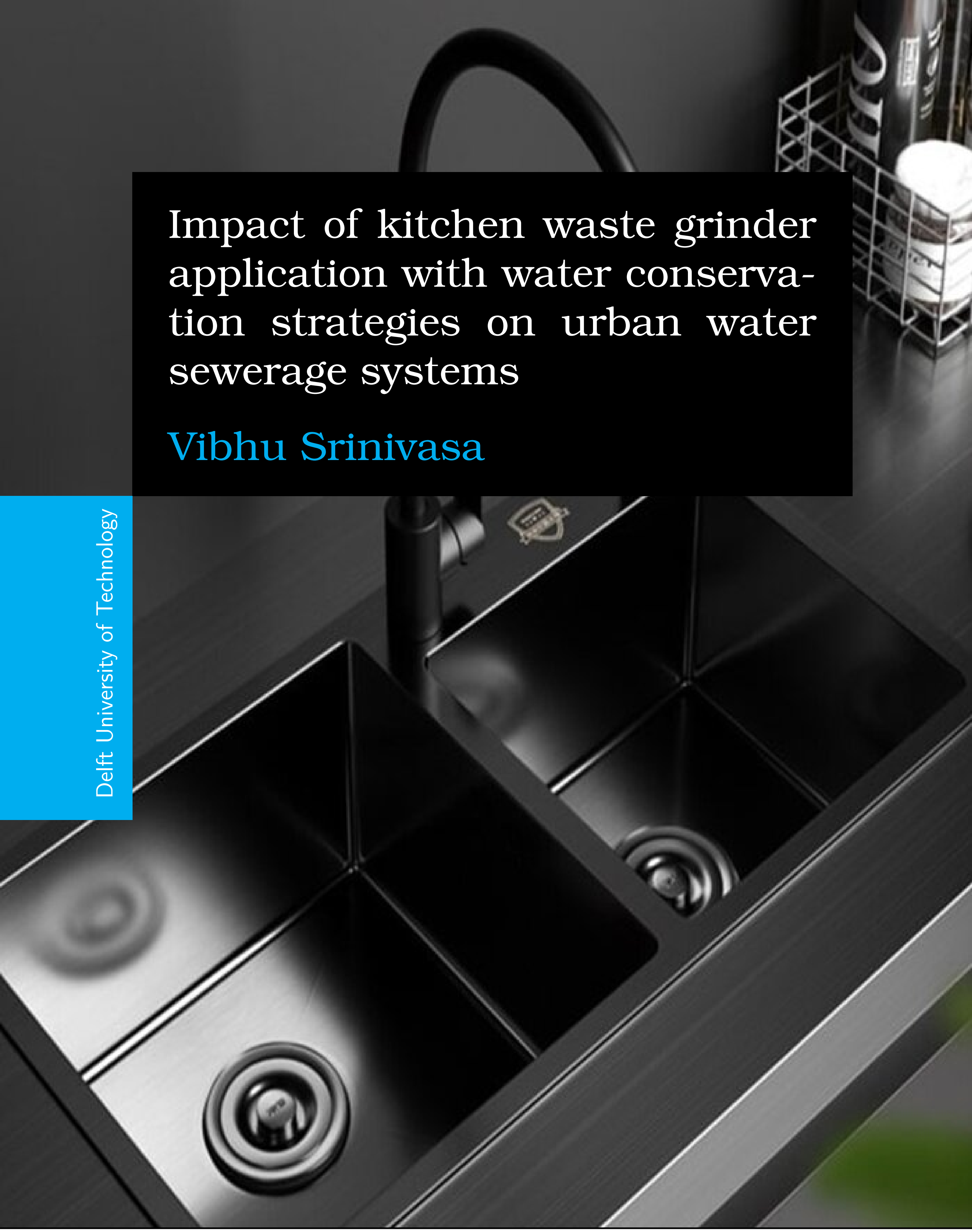

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by

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Abstract

Wastewater discharged from the domestic household has proven to be a potential source for resource recovery. Apart from wastewater, kitchen organic waste contains an enormous amount of energy in terms of organic content and nutrients such as Total Kjeldahl Nitrogen (TKN) and Total Phosphorous (TPH). Now that the disposal of waste into landfills is prohibited in most parts of Europe, one of the options is to divert the organic waste to wastewater treatment plants using kitchen waste grinders (KWG). Since KWG is a water-consuming appliance, the installation of KWG with water conservation technologies may be a viable option in the future. This can aid efficient recovery of resources and reduce the drinking water demand. The evolution towards sustainable urban sanitation will lead to several positive and negative effects. Some of the positive effects, apart from resource recovery, are the possibility to postpone the enlargement of existing sewer systems, to construct new sewers of smaller pipe diameter and to lower energy consumption for sewage pumping. While the negative effects are blockage of sewer due to reduced flow rates, increased sedimentation and release of malodor in the contemporary sewerage system and increased treatment costs due to increase in COD oxidation and nitrogen or phosphorus removal. Eventually the low flow-high load wastewater needs to be transported through sewers and treated locally (decentralised treatment). In this study, an attempt was made to investigate the effect of coupling the effluent from KWG at various penetration rates such as 100%, 75%, 50% and 25% with water conservation scenarios on hydraulic and quality parameters in the sewerage system. Water conservation scenarios were onsite greywater and rainwater reuse and application of ultra-low water demand appliances.

SIMDEUM® was upgraded with the addition of an extra appliance in the form of KWG to generate stochastic discharge patterns with appliance specific wastewater flows and quality. The data generated was incorporated into the sewer network model, InfoWorks ICM® to analyze the impact of the addition of KWG with water conservation strategies on the contemporary sewer network. The results obtained showed that there is an increase in the mass load of COD, TKN and TPH of 118%, 84% and 90% respectively and reduction in flow, velocity and shear stress of up to 54%, 49% and 74% respectively for the application of water conservation strategies with KWG. This substantiated the fact that the contemporary sewer system is not efficient in transporting the wastewater generated due to the addition

of KWG along with water conservation strategies at the household level. A new sewer design with smaller diameters and steep slopes was used to study if the low flow-high load wastewater can be safely transported, in terms of adequate self-cleansing velocity and shear stress. The results from the investigation of new sewer design showed that 100% and 75% implementation of KWG with water conservation technologies will achieve self-cleansing capacity which will help prevent clogging and sedimentation for a piping network of 110mm diameter at a slope of 1:160. KWG market penetration rates of lower than 50% along with water conservation strategies might face issues of sedimentation and clogging. In conclusion, the up-gradation of SIMDUEM® with KWG was successful to generate stochastic discharge patterns. This research has demonstrated that the application of KWG along with water conservation strategies may aid in resource recovery and reducing freshwater demand in the urban water cycle. The accomplishment of implementation of KWG with water conservation strategies is not realistic in the contemporary sanitary system however, this transition can be adopted in new urban developments with efficient design of wastewater transport and decentralized treatment system. Further research is required into the feasibility of a decentralised resource recovery system for the implementation of KWG with water conservation strategies.

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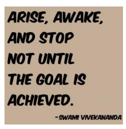

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Chapter 1

Introduction

Rapid urbanization and the growing demand of people due to changes in their lifestyles and practices have led to stress on resources. These resources include water, nutrients such as phosphorus and nitrogen and energy [1].

Water: The scarcity of freshwater is an increasing problem, even more, due to the use of pesticides, discharge of waste with pharmaceuticals, and personal care products and the effect of climate change [2]. Over the past years, researchers have found out that the stress on water scarcity in urban environments can be tackled with the use of water conservation and onsite reuse techniques [3]. The onsite reuse techniques include greywater reuse and rainwater harvesting. Furthermore, water can be conserved by using low water demand domestic appliances such as low flush toilets, smart showers and taps, low load washing machines and dishwashers [4].

Nutrients and energy: Phosphorus, nitrogen and potassium are some of the major nutrients that end up in domestic wastewater due to the use of above mentioned household appliances. Phosphate rock, a non-renewable resource is a non-substitutable raw material source in numerous products such as fertilizers, detergents and pharmaceuticals. More than 85% of mined phosphate rock is used for mineral fertilizer production (USGS, 2018). In this resource limiting setting wastewater has great potential as a source of phosphorus for recovery and recycling. The recovery from wastewater, more particularly from toilet or black water (BW) can contribute to approximately 22% of worldwide phosphorous demand [5]. The use of struvite precipitation is widely acknowledged in Europe and Japan for the recovery of phosphorus from wastewater treatment plants. Nitrogen on the contrary is not a non renewable resource due to its abundance in the atmosphere, however the procurement of nitrogen from the air using Haber-Bosch process is an energy intensive procedure consuming up to 37-45 $kJ.g^{-1}$ N [6]. Researchers in the past decade have come up with energy efficient removal and recovery of nitrogen from various wastewater streams. Some of which include removal of nitrogen using nitrification and anammox process for BW [7], recovery of nitrogen using microbial fuel cell from urine [8], algal growth [9] and applying photo-bioreactor for recovery of nitrogen and phosphorus from urine and BW [10].

Domestic wastewater is an ideal source for recovery of nutrients, but it also contains recoverable thermal energy. High amount of organic content (Chemical Oxygen Demand (COD)) present in wastewater makes it suitable for recovery of energy and the most common method is anaerobic digestion of wastewater to produce biogas composed mainly of methane (CH_4). Theoretically, 13.5 MJ CH_4/kgCOD removed can generate electrical energy of 1.5kWh [11].

Apart from the wastewater, a major component of household waste production is organic waste. In countries like the Netherlands organic kitchen waste makes up to 15% of 500 kg per capita per year of municipal solid waste [12]. The forbearance of disposal of organic waste into landfills (Directive 99/31 and council decision 19 December 2002 of the European Union) is in accordance with the European Environmental Agency's policy [13] of reducing the per capita waste production. Due to the high amount of moisture and organics present in food waste the co-treatment of organic kitchen waste with domestic wastewater has a lot of potential to enhance the recovery of important elements like nutrients (Total Kjeldahl Nitrogen (TKN) and Total Phosphorous (TPH)) and energy [14]. Unlike kitchen waste that has to be collected and transported as soon as possible, garden waste can be stored for a long time [15]. Separate garden waste can provide high quality compost at household level and it can also be collected and incinerated separately [16]. In countries like USA, Canada, Japan and Australia the most preferred option for channelizing the organic waste, majorly from the kitchen, to the wastewater treatment plant is the use of Kitchen Waste Grinder (KWG). The use of KWG can also solve the issues of food waste management and separate collection system such as reduction in emissions from refuse vehicles, drop in fuel consumption for collection and avoidance of cross contamination of kitchen and garden waste leading to better hygiene conditions in homes [17].

This chapter provides the background and literature study on various domestic appliances such as KWG, water saving and reuse technologies and the impacts associated with these changes on the sewer system.

1-1 Urban household appliances

1-1-1 Water saving appliances

The water use practices are changing among the urban population due to shortage of water, stringent regulations, growth in sustainable technology, modern economic and social trends [18]. Some of the sustainable appliance that can be used to reduce the domestic water consumption are low flush toilets, showers, taps, washing machines and dishwashers [19]. Agudelo-Vera et al (2014) carried out studies to determine the robustness of drinking water distribution network considering various future water demand scenarios. In their research new technological developments such as 100% penetration of vacuum toilets (1L per flush) was combined with the current situation. Under this scenario the water consumption was reported to be 92.2 L capita^{-1}day^{-1} where the actual demand was 132.8 L capita^{-1}day^{-1} in 2014.

Further innovation in technology with water efficient appliance such as smart taps, recycling showers, non-potable machines and 1.5 L flush toilets was reported by Artesia consulting (2018) on behalf of the Water Services Regulation Authority (Ofwat), UK. The water consumption was found to be 49 L capita^{-1}day^{-1} with all the innovative and sustainable alternatives. Research conducted by Parkinson et al (2005) concluded that sustainable water conservation strategy can be achieved only by the combination of all lower water demand appliances. Thus, a single source control strategy will not make a significant difference to reduce the water demand.

1-1-2 Greywater reuse

Greywater (GW) is defined as sewage generated from municipal appliances excluding the waste from toilet flushes. GW can be broadly classified into two types based on their streams namely light GW (bath, shower, wash basin and washing machine) and dark GW (kitchen sink and dishwasher) [20]. Onsite Greywater Reuse (GWR) can be considered as an efficient water saving alternative [21]. The treatment of GW is necessary to maintain the health and hygiene and minimize the negative effect on the environment [22] [23] [24]. The countries facing acute shortage of water use water reuse techniques the most. Up to 80%, 40% and 33% of domestic wastewater is reused in Israel, Malta, and Singapore respectively (World bank 2013). Research over the past decade have indicated that GWR for toilet flushing and garden irrigation can reduce the domestic household consumption up to 26% and 10%-41% respectively [3] [25].

1-1-3 Rainwater harvesting

Rainwater Harvesting (RWH) is an ancient and sustainable system of water collection and storage which can be dated back to 2000BC in the regions of present day Israel, Africa and India [26]. RWH is seen as a prominent water source alternative in many parts of the world to tackle the acute shortage of freshwater resources. The harvested rainwater can be utilised as a supplement for non-potable domestic usage such as water closet (WC) flushing or garden watering [27]. Various approaches haven been applied across the world in order to extend the RWH at household level. In metropolitan cities of India, Srilanka and Jordan with a very dense population, RWH is implemented via mandated regulation. On the other hand, in countries like Germany, Spain and Portugal government subsidies and rebate programs have been very effective in penetration of RWH at domestic level [28] [29]. In the Netherlands, the use of rainwater for residential use with waterless toilets can reduce the drinking water demand of 119 L capita^{-1}day^{-1} down by 29% [30].

1-1-4 Kitchen waste grinder

Kitchen waste grinders (KWGs) are small electronically powered macerators that are installed beneath the kitchen sink in between the sinks drain and the trap. Since 15% of the total amount of household waste represents grindable food waste, there is a large potential for the usage of KWGs [31]. KWGs grind the organic waste generated in the kitchen and flushes it into the sewer via the kitchen drain with a flow of cold water [32].

The usage of KWGs started in 1930s with USA being one of the largest users of them with penetration of more than 50% in households [33]. There have been continuous debates among the scientific community in Europe on the credibility and hazardous effects on the sewerage network. Installations in the European Member States (MS) is relatively low (around 5% penetration). All the MSs have discrete approach for handling non-hazardous waste depending upon the local authorities and citizens, the specification of wastewater treatment plants, intra-cultural considerations and penetrations of new technologies [34]. In fact, the disposal of kitchen waste is prohibited in the Netherlands if the effluent is connected to the sewer system to avoid potential loading impact on the sewer system [35]. Regardless, several research on KWG technology and its effect on the sewers and wastewater treatment systems in Europe have shown promising results of its application at household level [36] [16] [37] [33].

KWG water consumption rate (L $capita^{-1}day^{-1}$)	Source
4.48	[38]
4.5	[16]
1.01	[39]
3 - 4.5	[15]
2.32	[40]
4.38	[33]

Table 1-1: Water consumption rates for Kitchen waste grinder

The water consumption of KWG varies from 2.3 to 5 L $capita^{-1}day^{-1}$ depending on the manufacturer specification and total per capita use. A range of water consumption data from various research is shown in table 1-1.

Nutrient type	Nutrient loading range (g capita $^{-1}day^{-1}$) [36][40][35][16][31][OSKAR Project]
COD	72-121
TKN	0.5-2.5
TPH	0.03-0.25

Table 1-2: Per capita additional loading due to kitchen grinder application

The application of KWGs will increase the mass loading of nutrients in the sewers. Various studies show a range of inflow characteristics of nutrient loading in the sewers as shown in table 1-2. The instantaneous flow rate of 0.8-0.9 ls^{-1} was observed in the work of Butler and Davies (2011) and in EN-12056 [41].

Some of the positive implications identified by researchers for the diversion of kitchen waste to wastewater treatment plant using KWG include:

- Reduced space allocation for storage of food waste and reduction in noise created by solid waste collection vehicles [16].
- Improved health, hygiene and avoidance of disease-causing vectors due to storage [42].
- Economically viable option for the municipality due to reduction in waste collection amount by 40% and reduction in frequency [42] [43].
- Decrease in biochemical processes in landfills [35]
- High water and organic content in the effluent can help in enhanced biogas production in the wastewater treatment plant [16] [44]

- Installation of KWGs enhances the carbon to nitrogen ratio leading to better biological removal and cost reduction due to decreased methanol addition in wastewater treatment plants [40] [45].

However, there are studies that emphasized on some of the negative implications of discharging kitchen waste grinder effluent into the sewage system. Rosenwinkel and Wendler (2001) in their work, mentioned that KWGs will increase the water and energy consumption at household and wastewater treatment plant, increase the potential loading on combined sewer overflows. They have highlighted on increase in Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS) loading to the treatment plant which results in escalation of biosolids generation and disposal cost. This is supported by studies conducted by de Koning et al, 1999 and Kegebein et al, 2001 [16] [15]. The settling studies of food waste collected and grounded separately conducted by Philip Thomas (2011) showed that 62% of the total phosphorus and 90% of the ammonia was in the supernatant fractions, and approximately 77% and 90% of the TSS and Residual Suspended Solids (RSS) respectively were in the calculated sediment fractions. Some mass of TSS and RSS can be lost in the sewerage system and diluted low load approaching the centralised wastewater treatment plant. Hence the study indicates that alternative waste collection and treatment means can be implemented to recover most of the nutrients.

Legal situation for the use of kitchen waste grinders in the EU and The Netherlands

With the adoption of the landfill directive and aiming towards sustainable waste management, the use of kitchen waste grinders to recover organic waste is being encouraged in the European Member States [34]. This approach will also enhance the quality of sludge which can be used as agricultural supplements or can be anaerobically digested to obtain biogas. The advantages highlighted by studies and practical experiences for over 75 years have been recognized by the European Union very recently [34]. EU has established standards for both KWG unit (CENELEC EN 60335-1-16 and EN 55014) and the connecting pipes (CEN EN 12056-1:2000). The installation rates of KWGs are currently very low in Europe (approximately 1%) with the highest penetration of 5% in the Great Britain [46]. The MSs in accordance to the EU policy on non-hazardous waste have discrete legislation and policies on disposal techniques of organic waste. Countries like Ireland, UK and Italy do not have any restrictions on the use of KWGs. While in Sweden, Denmark and Finland permission is necessary from the local authorities responsible for sewer management for the installation of KWG. On the other hand, in Austria, Germany, Belgium, France, Luxembourg, Portugal and the Netherlands have prohibited the use of KWGs. The CECED report (2003) mentions that the ministry of environment, The Netherlands, stated that the legislation on ban of use of KWGs in the Netherlands is based on heuristic decision based on the fear of clogging in sewer system and decline in wastewater treatment efficiency and not based on scientific studies and experimental information [34].

1-2 Stochastic sewer modelling

Every urban household appliances mentioned in the previous section has unique functionality and water requirements. Hence, a model is necessary to analyse the water demand pattern based on changes caused to the end-use appliances individually. Efforts have been previously made to develop a model with a series of MATLAB codes for simulation of residential water demand based on appliance specifications, statistical and probabilistic information called SIMDEUM® [47]. SIMDEUM WW® was developed to demonstrate the possibility of pollutant discharge [48]. Further modification of SIMDUEM® and SIMDEUM WW® was carried out by Bailey et al, 2019 where the models were used for developing stochastic discharge patters with appliance specific discharge quality data. This model was incorporated in InfoWorks® to generate time-varying wastewater hydraulic and quality events to analyse the impact of water conservation techniques on the sewer system [49]. The predicted hydraulics and mass flow of nutrients were validated and it was found that InfoWorks® fails to detect time-varying suspended solids input and treats all the wastewater determinants as dissolved pollutants.

1-3 Resource load due to changes to input

The installation of water conservation technologies and KWGs can lead to increase in concentration of various resources such as COD, TKN, TKN and TSS present in wastewater [22] [50]. The changes in the quality of wastewater is explained further in this section with the help of various literature.

1-3-1 Due to water saving appliances, greywater reuse and rainwater harvesting

A very limited data is available on the wastewater characteristics of sewage from water saving appliances, GWR and RWH. However, some studies have generated data of domestic sewage using simulation modelling with sustainable water efficient technologies along with GWR and RWH. Penn et al., (2013), using SIMBA (Simulation Biologischer Abwassersysteme) have shown that the application of low flush toilets (6L and 3L for full and half flush respectively) coupled with GWR will result in a wastewater discharge of 102 L capita^{-1}day^{-1} for a population of 15,000. The nutrient loads due to GWR for toilet flushing is shown in table 1-3. A similar study on predicting impact of water conservation strategies with a stochastic model was done by Bailey et al., 2020 using SIMDEUM WW® as shown in table 1-3. The values were predicted for a population of 418 households (1.7 person per household) with a wastewater discharge of 80 L capita^{-1}day^{-1}. Similar values were found in works of Henze et al., 2008 and Tchobanoglous and Burton., 1991 [51] [11].

Nutrient type	Nutrient loading range (g capita $^{-1}$day^{-1}) for	
	102 L capita^{-1}day^{-1} [3]	80 L capita^{-1}day^{-1} [50]
COD	137	86-122
TKN	2.8	8-12
TPH	10	0.8-1.2

Table 1-3: Per capita mass loading of COD, TKN and TPH due to water conservation appliances and practises

1-3-2 Due to Kitchen waste grinders

The concentration of of COD, TSS, TN and TP in wastewater after addition of KWG is shown in Table 1-4. In a lab scale study performed by Bolzonella et al (2003) [40], the organic fraction collected from municipal solid waste was combined with real wastewater. The typical vales of TSS, COD, TN and TP was observed to be 110 mg.L^{-1}, 150 mg.L^{-1}, 36.8 mg.L^{-1} and 2.9 mg.L^{-1}. The similar values were found to be in studies performed by de Koning et al., 1999, Kubler et al., 2000 and Thomas., 2011 as shown in table 1-4[16] [52] [53]. These values are also similar to the low strength wastewater prescribed in Metcalf and Eddy (1991) [11]. Further a case study was performed by Battistoni et al (2007) [36] in a small village called Gagloile, in central Italy with domestic kitchen grinder (95 persons) and an industrial kitchen grinder (60 persons) in the local school. The inflow characteristics of sewage with addition of ground kitchen waste in dry weather conditions was observed to be as follows: TSS: 223 mg.L^{-1}, COD: 827 mg.L^{-1}, TN: 69 mg.L^{-1} and TP: 6 mg.L^{-1} as shown in table 1-4.

Nutrient type	Concentration (mg.L $^{-1}$)	
	[16][40][52][53]	[36]
COD	150	827
TSS	110	223
TN	36.8	69
TH	2.9	6

Table 1-4: Concentration of COD, TSS, TN and TP in wastewater after addition of KWG

1-4 Impact on sewer due to changes to input

The domestic sewage generated from these household appliances needs to be transported through sewers to recipients such as wastewater treatment plants or close by water bodies. Contemporary sewers are designed for the conveyance of wastewater and stormwater from urban areas. They are sized based on rainfall events, population forecast (sewage flows estimation) and groundwater infiltration for different design periods depending on the countries [12] [54]. The use of water efficient domestic appliances and reuse techniques may lead to decreased flow, velocity and depth in the contemporary sewers. Significant increase in the nutrient load such as COD, TSS, TN and TP was observed in the sewers [19]. The study conducted by Bailey et al, 2019 have shown that 15%-60% reduction in water demand will result in 5%-50% drop in overnight and day time peak flows [49]. The urban lifestyles and water use practices could also lead to the transition in diurnal wastewater discharge patterns [55]. The assessment of the impact of GWR and water efficient technologies conducted by Penn et al (2013) [3] showed that the velocity of the output from these technologies fall still within the range of the self-cleansing velocity (0.6 ms^{-1} to 1.0 ms^{-1} [56]) for solids movement. However, they concluded that with 33% household implementing these technologies the upstream section of the sewers tends to have blockages. Stochastic sewer modelling study conducted by Bailey et al, 2019 showed street scale pipes of 150mm diameter showed stagnation due to lower water demand and reuse appliances [49].

One of the most debatable impact due to the discharge of kitchen waste into the sewers are overflow, increased clogging and bad odors [53]. The input of kitchen waste to sewers will most likely cause problems in upstream sections of the sewers called the laterals [57]. Some of the methods used to inspect the suspended solids accumulation in the sewers are videotaping and photography [58]. Marashlian (2005) in their study used the videotaping approach to inspect the impact of kitchen waste on the sewers. Clogging was not observed in the kitchen sewer connecting pipe (3.2 cm - 5.1 cm in diameter) and sewer lines (0.4 m – 2.0 m in diameter) in the study. But a buildup of sewage with a thickness of 0.5-1.5 cm on the surface at water level with a width of 2 cm to 3 cm was reported. The grain size, density and settling velocity are the physical parameters that determine the clogging in sewers due to solids. The data from various manufacturers show that 91% of solids in disposer effluent are less than 1mm in size (CRC 2000). The sedimentation of kitchen waste is unlikely to happen due to density as ground organic particle's specific gravity (less than 2) is lower than the specific density of water [59]. But larger particles such as egg shells, bones and fish with specific gravity of more than 2 can settle in the sewers [40] [39] [15]. A self-cleansing velocity of 0.5 ms^{-1} to 1.6 ms^{-1} for sewers with diameter of 200 mm to 2000 mm was observed to be sufficient enough to avoid settling problems in the sewer lines [15] [40] [44]. Studies done by Rosenwinkel et al., 2001 and Mattsson et al., 2014 [60] have suggested a minimum gradient of 2% in pipes to avoid deposition. But research in countries like The Netherlands, where the gradient of most of the sewer pipes are shallow (<2%) no evidence of clogging was found [16].

Apart from settling solids many researchers have identified that fat, oil and grease (FOG) deposits found in the sewers can be a reason of clogging. Application of KWGs is not a major contributor to formation of FOG deposits [60], however use of cold water in the KWGs will avoid the FOG attachment in the sewer pipes [46]. The disposal of protein rich food waste and growth of biofilms in the sewers are attributed to be the cause for release of odorous gases such as H_2S and volatile organic compounds [61] [62]. These gases lead to corrosion in pipes if the pH is lower than 5.6 [63]. In order to avoid odor issues and mitigate corrosion Jiang et al., (2015) [61] have suggested the dosing of nitrate or iron salts to the sewers and use of corrosion resistant pipes to the new sewer lines.

1-5 New sewer design

In the recent past, most of the modern sewer designs are focusing on separate sewer systems, where sanitary wastewater is collected separately from storm water runoff [11]. The new design of sewer system with smaller pipe diameters and steeper slopes will predominantly aid in transporting low flow-high load wastewater by achieving critical velocity and necessary shear stress[64]. A paradigm shift towards the use of low water consuming appliance and generation of concentrated domestic wastewater has been noticed over the past decade. This shift persuaded many researchers to conduct characterisation of concentrated slurry and investigate the impact mentioned in Section 1-4 on sewers. The study conducted by Memon et al., 2007 [64] shows that modifications to wastewater collection systems with small diameter sewer pipes and higher gradients will significantly aid in resolving the issues of solids transport in low flush volumes.

Two basic criteria that are established at a specific depth of flow are minimum velocity and minimum shear stress to achieve non-zero deposition conditions in a sewer system [65].

Different countries have minimum velocity standards ranging from 0.30 $m.s^{-1}$ to 0.75 $m.s^{-1}$. However, the European standard, EN-752-4 [41], states that 0.70 $m.s^{-1}$ of minimum velocity is necessary once a day to avoid sedimentation in foul sewer system. The minimum shear stress values vary worldwide over a range of 2-4 $N.m^{-2}$ [41] [65]. Apart from the minimum velocity and minimum shear stress different parameters need to be considered to design a new sewer system. These parameters include concentration and size of sediments, diameter of the pipe, depth of the flow, gradient and roughness of the pipe [66].

Chapter 2

Problem Definition

2-1 Knowledge gap

In order to help alleviate the water crisis a total area reform with 100% implementation of lower water demand domestic appliances such as low flush toilets, taps, washing machines, showers and dishwashers in all the urban households is encouraged [67]. The reduction in water demand and use of on-site greywater reuse and rainwater harvesting strategies will have significant increase in nutrient loading on the sanitary system which can aid in recourse recovery [50]. A positive impact towards achieving efficient resource recovery can be accomplished by integration of kitchen waste grinders along with water conservation strategies in urban localities [68]. But these strategies may have a significant impact on the hydraulic and quality parameters of wastewater in the sewers as shown in the section 1-3 and section 1-4. Therefore, there is a clear need for a detailed study on these parameters for the combination of KWG and water conservation strategies in the sewerage system.

Until now there is a very limited effort in developing stochastic sewer model of high organic load from KWGs along with water conservation techniques. The development of integrated stochastic sewer model using SIMDEUM ® and InfoWorks ICM® (sewer edition) has proven to be a competent tool for predicting accurate flows, depths, velocities and mass flow of nutrients in the sewers with divergent water conservative future scenarios [50]. However, there are certain limitations like omission of certain appliances such as KWGs which is a viable choice for resource recovery. These limitations can be justified by considering the fact that SIMDEUM® is developed in the Netherlands where KWG is not considered as a common appliance at household level due to the prohibition on the discharge of kitchen waste effluent in to the sewers.

2-2 Objective

The main objective of this thesis is to examine the impact of a large-scale application of the KWGs on wastewater hydraulic and quality parameters in an urban sewerage system with water conservation strategies. Detailed objectives of this study are as follows:

1. Incorporation of a new appliance in the form of KWG in SIMDEUM® to generate stochastic demand patterns and conversion into wastewater discharge pattern using SIMDEUM WW®.
2. To study the impact on wastewater quality parameters (such as COD, TKN and TPH) dynamics if different penetration rates of the application of KWGs are considered (i.e., 100%, 75%, 50% and 25%) along with 100% implementation of water conservation and reuse strategies.
3. To study the impact on wastewater hydraulic parameters (such as velocity, depth and shear stress) if different penetration rates of the application of KWGs are considered (i.e., 100%, 75%, 50% and 25%) along with 100% implementation of water conservation and reuse strategies.
4. To examine the effect of the integration of KWGs with water conservation and reuse strategies on wastewater hydraulic and quality parameters in new sewer design network.

2-3 Approach

The approach followed to achieve the objectives are as follows:

1. The up-gradation of SIMDEUM® for the application of kitchen waste grinder along with other water saving and reuse technologies. These patterns are developed based on appliance usage frequency, water demand and discharge of nutrients per usage found in literature.
2. The application of stochastic discharge patterns in sewer model to analyse the hydraulic and quality impact on the contemporary sewer system due to the use of KWG in combination with water conservation strategies. Based on the consequences, a new sewer network with advised design criteria will be incorporated into the sewer model to safely transport concentrated domestic wastewater.

2-4 Research questions

The main research question is:

"What impact can addition of kitchen waste grinder effluent in combination with water conservation technologies have on the sanitary sewerage system?"

The sub-questions include:

1. Can a stochastic demand and discharge pattern be generated for KWG in combination with water conservation strategies?
2. Does application of kitchen waste grinder coupled with water saving strategies increase nutrient loading such as COD, TKN and TPH in traditional sanitary sewerage system?

3. Does it reduce the flow, velocity and shear stress in the traditional sanitary sewerage system?

4. In case it does, what can be done to safely transport this low-flow, high-load wastewater?

2-4-1 Hypothesis

In order to address the research questions a hypothesis is made for further investigation as follows: "TO safely transport low-flow high-load, that is for instance generated by the combination of KWG and water conservation strategies, new sewer design principles are needed".

Chapter 3

Methodology

3-1 Household demand pattern

All the urban household appliances differ in their water demand and serviceability. A series of MATLAB® codes in SIMDEUM® is used to generate stochastic household demand patterns based on the discharge probability of different appliances [48]. These set of codes is developed or modified for the addition of an extra appliance in the form of a kitchen waste grinder. The physical addition is as shown in figure 3-1.

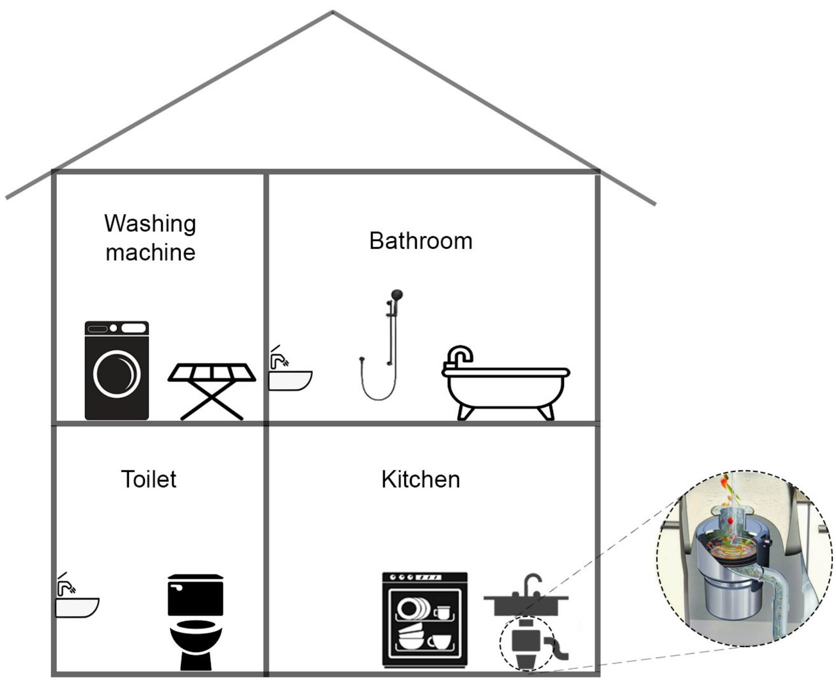

Figure 3-1: Standard domestic water demand appliances along with Kitchen Waste Grinder

The flowchart for the addition of KWG with standard end-use appliances in a domestic household to generate stochastic demand patters using SIMDEUM® is shown in figure 3-2. The KWG is defined as an end use appliance at different penetration rates. The penetration rate of 100%, 75%, 50% and 25% is used in the current study. A higher penetration rate of KWG is considered assuming that in future all the household will use KWG as an option to dispose kitchen waste.

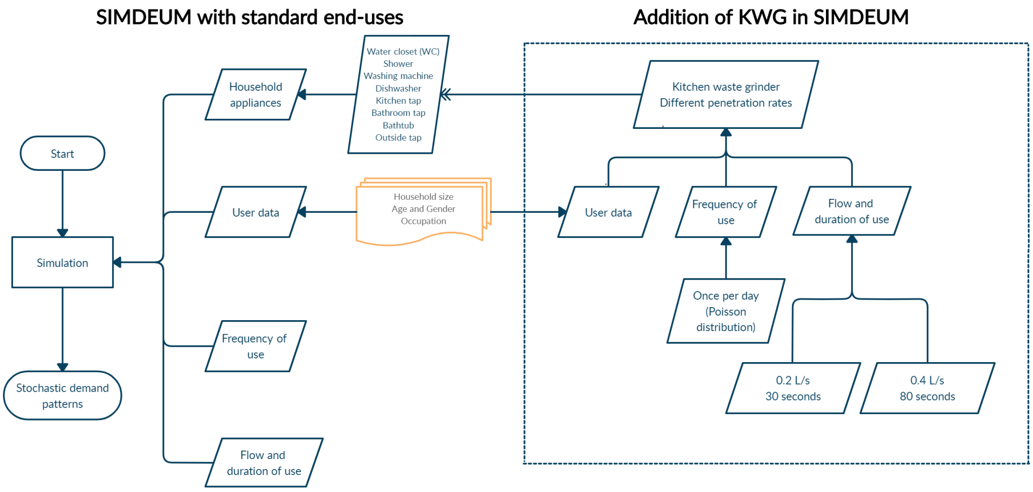

Figure 3-2: Logic flowchart for the addition of kitchen waste grinder in SIMDEUM®. SIMDEUM® for standard end-use is adapted from Blokker et al., 2010

The data on end users is an important input to generate demand patterns which can be obtained by governmental organisations dealing with population survey. Figure 3-3 shows the future population statistics for the city of Amsterdam obtained from Gemeente Amsterdam. The average occupancy in Amsterdam is predicted to be 1.81 (Max. occupancy). By considering this as the maximum bound, a minimum bound of 1.15 (Min. occupancy) is considered for this research (Appendix A-1).

The frequency of usage of KWG is considered as once per person per day [69]. It is assumed to follow Poisson distribution since the event occurs one time at a fixed interval of time with a constant mean rate. Two category of values were considered in this study based on flow and flush duration. The minimum usage scenario with a flow of 0.20 $L.s^{-1}$ and flush duration of 30 seconds [69]. While on the contrary the maximum usage values were significantly higher, with a flow of 0.40 $L.s^{-1}$ and flush duration of 72 seconds. The MATLAB code in SIMDEUM® for KWG is developed in line with other household appliances developed by the Blokker et al, 2010 [48]. Once the information on population statistics, occupancy and appliance characteristics are applied into the model, the simulation is run to obtain stochastic demand pattern per household.

3-2 Household discharge pattern and sewer modelling

The discharge flow patterns generated from SIMDEUM® is converted into appliance specific wastewater quality pattern using SIMDUEM WW®. This is adapted from modified and

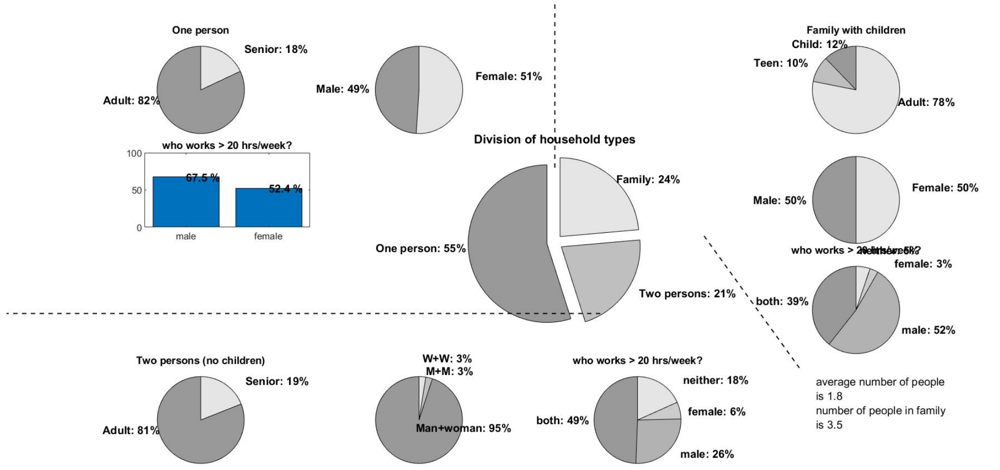

Figure 3-3: Predicted future household statistics used in SIMDEUM®

validated SIMDEUM WW® used by Bailey et al, 2019 [49] but with the addition of Kitchen waste grinder as an extra appliance. The typical mass loading of nutrients from kitchen waste is, for instance, derived from de Koning et al, 1996 [16] and Bolzonella et al, 2003 [40] as shown in table 3-1. The values of mass loading of nutrients for other appliances with GWR and RWH is adapted from Bailey et al, 2020 [50] as shown in table A-1.

Appliance	Water demand L capita^{-1}day^{-1}	Effluent g use^{-1}			Discharge Temperature (^{o}C)	Source
		COD	TKN	TPH		
KWG- Min. usage	6	38	1.5	0.05	20	[16] [36]
KWG- Max. usage	28.8					

Table 3-1: Water demand and mass load of nutrients for KWG

Further the wastewater discharge profiles generated using SIMDUEM WW® is converted to .csv files and used as an input for the sewer model, InfoWorks ICM®(Sewer edition; Innovyze Ltd, Oxfordshire). The hydraulic and water quality simulation occurs together in InfoWorks ICM®. It calculates the concentration of pollutants and suspended sediments along with drift and deposition of the sediment in each conduit of the drainage system at defined time step.

3-3 Model analysis

The developed sewer model is used to analyse the impact on hydraulic and quality parameters of the future scenarios. The future water conservation comprised of the following scenarios:

- ECO scenario, the disposal of the effluents from KWG along with the ECO scenario adapted from the work of Agudelo-Vera et al., 2015 comprises of the discharge from water efficient appliances such as 1L flush toilets, smart shower and tap components and waterless washing machines and dishwashers. This scenario portrays complete transition towards innovation. The water demand for this scenario is shown in table 3-2

- GWR scenario utilises the treated greywater for toilet flushing and washing machines. The greywater feed quality data derived from various literature is shown in table A-1.
- RWH scenario utilises the treated rainwater for toilet flushing and washing machines. The rainwater feed quality data derived from various literature is shown in table A-1.

The water demand for future scenarios is shown in table 3-2.

Scenario	Water demand (lpcd)	
	Min. usage of KWG [69]	Max. usage of KWG
1- Baseline	112	
2a- ECO, Max. occupancy	47.6	70.4
2b- ECO, Min. occupancy	49.4	72.2
3a- GWR, Max. occupancy	72.9	95.7
3b- GWR, Min. occupancy	74.0	96.8
4a- RWH, Max. occupancy	72.9	95.7
4b- RWH, Min. occupancy	74.0	96.8

Table 3-2: Water demand of future scenario

3-3-1 Existing sewer network

The modelling approach has proven to be successful in generating a stochastic sewer model to analyses the hydraulic parameters and mass loading of nutrients due to conservation techniques by Bailey et al., 2020 [50]. Now it is used to analyze the effect of addition of ground kitchen waste into the sewers along with the other household components and future water saving options. The catchment used to analyse the existing sewer design is Prinseneiland, an area located in the northwest of Amsterdam city shown in figure 3-4. Prinseneiland is cho-

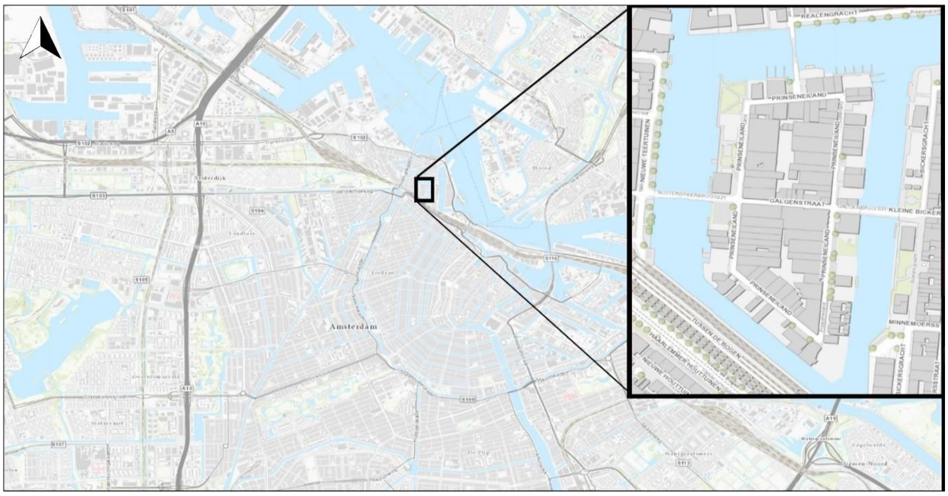

Figure 3-4: Map of Prinseneiland, Amsterdam (Source: Waternet, Amsterdam)

sen as it has well defined boundaries, measurement availability and simple combined sewer system. It is a residential area with 694 inhabitants and 50 small businesses (Waternet). Around 418 residential connections is available based on the data collected from Waternet, Amsterdam. The data on non-residential connections is not used since the demand patterns were generated for residential buildings. The combined sewer network comprised of concrete pipes with a diameter of 400–600mm and slope ranging from 1:1961 to 1:133, average slope being 1:615. The simulation is conducted for 5 days with a thirty second time step in the current study. The model is simulated for a dry weather flow condition ignoring rainwater and groundwater infiltration.

3-3-2 New sewer network

The new sewer network adopted in this study is based on the two basic criteria established at a specific depth of flow are minimum velocity and minimum shear stress to achieve non-zero deposition conditions in a sewer system. In order to achieve this a hypothetical area with a population of 418 household and a separate sewerage system is considered to simulate the developed sewer model. The specifications for diameter and slope were considered based on data obtained from published works of Memon et al, 2007 [64], Penn et al, 2013 [3] and Bailey et al, 2020 [50] in order to safely transport stochastic flow of high load wastewater as discussed in section 1-5. The three combinations of new sewer network is used in this research in the same order as mentioned below. The lowering of diameter and slope is followed to achieve an optimised new sewer network with self cleansing capacity.

1. 160mm diameter and slope of 1:250
2. 110mm diameter and slope of 1:250
3. 110mm diameter and slope of 1:160

The household occupancy is used as mentioned in section 3-1 and water demand is considered as mentioned in table 3-2. The mass load of nutrients is considered as shown in section 3-2 for the prediction of hydraulic quantity and quality in the sewer system.

Chapter 4

Results

4-1 Hydraulic and quality modelling for the existing sewer network

The effect of addition of KWG along with complete area reform (100% implementation) of water conservation technologies on hydraulic and quality parameters was tested using six future scenario mentioned in table 3-2. The hydraulic and quality parameters were observed at the location as shown in figure 4-1. This was done by using stochastic discharge patterns

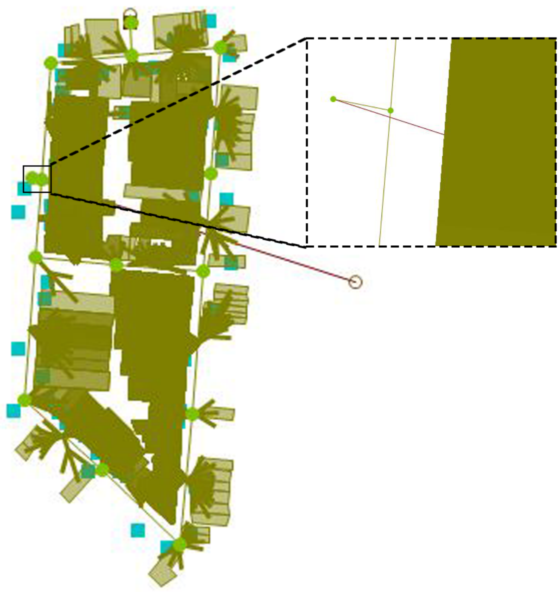

Figure 4-1: Sewer location for the observation of hydraulic and quality parameters in the catchment area

with sewer model at various market penetration rates of KWG for the existing sewer network.

4-1-1 100% market penetration rate of KWG

The five day quantitative average of flow, velocity and shear stress due to the 100% penetration rate of KWG (maximum and minimum usage) along with 100% implementation of water conservation strategies is shown in table 4-1. It can be observed that 100% implementation of

		Maximum usage						**Minimum usage**					
	Baseline	ECO Max	ECO Min	GWR Max	GWR Min	RWH Max	RWH Min	ECO Max	ECO Min	GWR Max	GWR Min	RWH Max	RWH Min
Flow ($L.s^{-1}$)	3.03	2.77	1.95	2.59	1.86	4.24	2.90	2.84	1.50	1.90	1.46	3.59	2.34
% change from baseline		*-8%*	*-36%*	*-14%*	*-39%*	*40%*	*-4%*	*-6%*	*-50%*	*-37%*	*-52%*	*19%*	*-23%*
Velocity ($m.s^{-1}$)	0.28	0.20	0.17	0.19	0.17	0.22	0.19	0.21	0.17	0.17	0.15	0.23	0.20
% change from baseline		*-31%*	*-41%*	*-33%*	*-42%*	*-21%*	*-32%*	*-24%*	*-41%*	*-41%*	*-48%*	*-18%*	*-31%*
Shear stress ($N.m^{-2}$)	0.82	0.35	0.28	0.34	0.28	0.43	0.35	0.44	0.31	0.28	0.24	0.49	0.38
% change from baseline		*-57%*	*-65%*	*-59%*	*-66%*	*-47%*	*-58%*	*-47%*	*-63%*	*-66%*	*-71%*	*-40%*	*-53%*

Table 4-1: The effect of 100% implementation of KWG (maximum and minimum usage) with water conservation technologies on hydraulic parameters at the catchment outfall of the existing sewer network. Each parameter in the future scenario is compared with the baseline scenario with data simulated for a working week.

water conservation technologies with KWG will significantly reduce the flow rate by 6%-52%. Visual inspection of Appendix B-1a and Appendix B-2a for maximum and minimum usage of KWG respectively shows lower variability in diurnal wastewater flow patterns. The shear stress values for addition of KWG along with water conservation technology at the catchment outfall was predicted to be in the range of 0.24 – 0.44 $N.m^{-2}$ and the velocity range of 0.17 – 0.23 $m.s^{-1}$. The cumulative frequency graph for shear stress and velocity for maximum and minimum usage of KWG in comparison to the baseline scenario can be seen in Appendix B-1b and c and Appendix B-2b and c respectively.

Mass load per capita	**100%**	**75%**	**50%**	**25%**
COD ($g.day^{-1}$)	115.19 – 194.63	91.76 – 187.96	98.42 – 163.72	59.5 – 165.48
TKN ($g.day^{-1}$)	10.52 – 14.48	7.40 – 13.85	7.40 – 13.12	4.76 – 13.32
TPH ($g.day^{-1}$)	0.96 – 1.45	0.87 – 1.38	0.77 – 1.18	0.38 – 0.79

Table 4-2: Quantifying the impact due to implementation of KWG with water conservation technologies at various penetration rates on quality parameters at the catchment outfall of the existing sewer network

The mass load of nutrients per person per day for 100% implementation of KWG along with different water conservation and reuse technologies ranged from 115.9 – 194.65 g COD, 10.52 – 14.48 g TKN and 0.96 – 1.45 g TPH as shown in table 4-2. The cumulative frequency of COD, TKN and TPH concentration in 100% penetration of KWG (maximum and minimum usage) wastewater along with water conservation strategies at the catchment outfall over 5 days can be found in Appendix B-1 and Appendix B-2.

4-1-2 75% market penetration rate of KWG

The quantitative effect of implementation of KWG (maximum and minimum usage) at 75% penetration rate with 100% implementation of water conservation technologies on hydraulic

	Baseline	Maximum usage						Minimum usage					
		ECO Max	ECO Min	GWR Max	GWR Min	RWH Max	RWH Min	ECO Max	ECO Min	GWR Max	GWR Min	RWH Max	RWH Min
Flow ($L.s^{-1}$)	3.03	2.38	1.74	2.36	1.71	4.11	2.75	2.04	1.40	1.97	1.42	3.36	2.45
% change from baseline		*-21%*	*-43%*	*-22%*	*-44%*	*36%*	*-9%*	*-33%*	*-54%*	*-35%*	*-53%*	*11%*	*-19%*
Velocity ($m.s^{-1}$)	0.28	0.20	0.17	0.18	0.16	0.22	0.19	0.20	0.17	0.17	0.15	0.20	0.18
% change from baseline		*-31%*	*-41%*	*-35%*	*-44%*	*-22%*	*-33%*	*-31%*	*-41%*	*-40%*	*-48%*	*-29%*	*-37%*
Shear stress ($N.m^{-2}$)	0.82	0.32	0.26	0.32	0.26	0.42	0.34	0.29	0.23	0.29	0.23	0.38	0.32
% change from baseline		*-61%*	*-68%*	*-61%*	*-68%*	*-48%*	*-59%*	*-64%*	*-72%*	*-65%*	*-71%*	*-54%*	*-62%*

Table 4-3: The effect of 75% implementation of KWG (maximum and minimum usage) with water conservation technologies on hydraulic parameters at the catchment outfall of the existing sewer network. Each parameter in the future scenario is compared with the baseline scenario with data simulated for a working week.

parameters in comparison with the baseline scenario at the catchment outfall of the existing sewer network can be found in table 4-3. It can be observed from the results the flow rate rate reduction of 9%-54% due to application of water conservation technologies along with 75% penetration of KWG installations. The penetration rate of 75% of KWG along with water conservation technologies showed similar results as shown in section 4-1-1 with low variability in diurnal wastewater flow patterns. This can be observed in Appendix B-3a and Appendix B-4a for maximum and minimum KWG usage respectively. The values of shear stress and velocity was found to be in the range of 0.23 – 0.38 $N.m^{-2}$ and 0.15 – 0.22 $m.s^{-1}$ respectively.

The average nutrient mass loading rate per person per day for 5 working day simulation for 75% implementation of KWG along with 100% implementation of different water conservation and reuse technology ranged from 91.76 – 187.96 g COD, 7.40 – 13.85 g TKN and 0.87 – 1.38 g TPH as shown in table 4-2. The graphical representation in Appendix B-3 and Appendix B-4 shows in detail the effect of 75% implementation of maximum KWG usage and and minimum KWG usage respectively, with water conservation technologies on hydraulics and quality parameters at the catchment outfall of the existing sewer network.

4-1-3 50% market penetration rate of KWG

The quantitative effect of 50% implementation of KWG (maximum and minimum usage) with water conservation technologies on hydraulic parameters in comparison with the baseline scenario at the catchment outfall of the existing sewer network can be found in table 4-4 in detail.

	Baseline	Maximum usage						Minimum usage					
		ECO Max	ECO Min	GWR Max	GWR Min	RWH Max	RWH Min	ECO Max	ECO Min	GWR Max	GWR Min	RWH Max	RWH Min
Flow ($L.s^{-1}$)	3.03	2.32	1.61	2.12	1.59	2.37	2.59	2.07	1.44	1.82	1.42	3.44	2.37
% change from baseline		*-23%*	*-47%*	*-30%*	*-48%*	*-22%*	*-15%*	*-31%*	*-53%*	*-40%*	*-53%*	*14%*	*-22%*
Velocity ($m.s^{-1}$)	0.28	0.18	0.16	0.18	0.15	0.18	0.18	0.17	0.15	0.16	0.15	0.20	0.18
% change from baseline		*-36%*	*-46%*	*-39%*	*-46%*	*-38%*	*-35%*	*-39%*	*-48%*	*-42%*	*-48%*	*-28%*	*-38%*
Shear stress ($N.m^{-2}$)	0.82	0.32	0.25	0.30	0.25	0.31	0.33	0.29	0.24	0.27	0.23	0.38	0.31
% change from baseline		*-62%*	*-69%*	*-64%*	*-70%*	*-63%*	*-60%*	*-64%*	*-71%*	*-67%*	*-71%*	*-54%*	*-63%*

Table 4-4: The effect of 50% implementation of KWG (maximum and minimum usage) with water conservation technologies on hydraulics and quality parameters at the catchment outfall of the existing sewer network. Each parameter in the future scenario is compared with the baseline scenario with data simulated for a working week.

It can be observed that 100% implementation of water conservation technologies along with 50% penetration of KWG will significantly reduce the flow rate by 15%-53%. The penetration rate of 50% of KWG along with water conservation technologies will further lower the variability in diurnal wastewater flow patters as compared to 100% and 75% penetration rate of KWG. This can be observed in Appendix B-5a and Appendix B-6a for maximum and minimum KWG usage respectively. The shear stress values for addition of KWG along with water conservation technology at the catchment outfall was observed to be in the range of 0.24 – 0.38 $N.m^{-2}$ and the velocity range of 0.15 – 0.20 $m.s^{-1}$. The cumulative frequency graph for shear stress and velocity for maximum and minimum usage of KWG in comparison to the baseline scenario can be seen in Appendix B-5b and c and Appendix B-6b and c respectively.

The average nutrient mass loading rate per person per day for 5 working day simulation for 50% implementation of KWG along with 100% implementation of different water conservation technology ranged from 98.42 – 163.72 g COD, 7.40 – 13.12 g TKN and 0.77 – 1.18 g TPH as shown in table 4-2. The graphical representation in Appendix B-5 and Appendix B-6 shows in detail the effect of 50% implementation of maximum KWG usage and and minimum KWG usage respectively, with water conservation technologies on hydraulics and quality parameters at the catchment outfall of the existing sewer network.

4-1-4 25% market penetration rate of KWG

The quantitative effect of implementation of KWG (maximum and minimum usage) with water conservation technologies on hydraulic parameters in comparison with the baseline scenario at the catchment outfall of the existing sewer network can be found in table 4-5 in detail.

	Baseline	Maximum usage						Minimum usage					
		ECO Max	ECO Min	GWR Max	GWR Min	RWH Max	RWH Min	ECO Max	ECO Min	GWR Max	GWR Min	RWH Max	RWH Min
Flow ($L.s^{-1}$)	3.03	2.07	1.53	1.91	1.40	3.53	2.56	1.93	1.39	1.77	1.39	3.44	2.47
% change from baseline		*-32%*	*-49%*	*-37%*	*-54%*	*16%*	*-15%*	*-36%*	*-54%*	*-42%*	*-54%*	*14%*	*-18%*
Velocity ($m.s^{-1}$)	0.28	0.17	0.15	0.17	0.15	0.21	0.18	0.17	0.15	0.16	0.15	0.20	0.18
% change from baseline		*-39%*	*-47%*	*-41%*	*-49%*	*-27%*	*-36%*	*-41%*	*-49%*	*-43%*	*-49%*	*-28%*	*-37%*
Shear stress ($N.m^{-2}$)	0.82	0.29	0.24	0.28	0.23	0.39	0.32	0.28	0.23	0.27	0.23	0.38	0.31
% change from baseline		*-64%*	*-70%*	*-66%*	*-72%*	*-52%*	*-61%*	*-66%*	*-72%*	*-67%*	*-72%*	*-54%*	*-62%*

Table 4-5: The effect of 25% implementation of KWG (maximum and minimum usage) with water conservation technologies on hydraulics and quality parameters at the catchment outfall of the existing sewer network. Each parameter in the future scenario is compared with the baseline scenario with data simulated for a working week.

It can be observed that 100% implementation of water conservation technologies with 25% penetration rate of KWG will significantly reduce the flow rate by 15%-54%. The penetration rate of 25% of KWG along with water conservation technologies has the lowest variability in diurnal wastewater flow patters as compared to other penetration rates of KWG as shown in Appendix B-7a and Appendix B-8a for maximum and minimum KWG usage respectively. The shear stress values for addition of KWG along with water conservation technology at the catchment outfall was predicted to be in the range of 0.23 – 0.39 $N.m^{-2}$ and the velocity range of 0.15 – 0.20 $m.s^{-1}$. The cumulative frequency graph for shear stress and velocity for maximum and minimum usage of KWG in comparison to the baseline scenario can be seen in Appendix B-7b and c and Appendix B-8b and c respectively.

The average nutrient mass loading rate per person per day for 5 working day simulation for 25% implementation of KWG along with 100% implementation of different water conservation technology ranged from 59.50 – 165.48 g COD, 4.76 – 13.32 g TKN and 0.38 – 0.79 g TPH as shown in table 4-2. The graphical representation in Appendix B-7 and Appendix B-8 shows in detail the effect of 25% implementation of maximum KWG usage and and minimum KWG usage respectively, with water conservation technologies on hydraulics and quality parameters at the catchment outfall of the existing sewer network.

4-2 Hydraulic and quality modelling of new sewer design

The effect of addition of KWG along with water conservation technologies on hydraulic and quality parameters were carried out using three different set of new sewer networks based on the design criteria mentioned in section 1-5. Simulations were conducted for six future scenario mentioned in table 3-2 using stochastic water demand and wastewater quality models at various market penetration rates of KWG and complete area reform (100% implementation of water conservation strategies).

4-2-1 Pipe network of 160mm diameter and slope of 1:250

The maximum velocity, maximum depth and maximum shear stress achieved in this sewer network on implementation of KWG at various penetration rates along with 100% implementation of water conservation technologies at the catchment outfall is shown in table 4-6 in detail.

	100%						**75%**					
	KWG Min usage			**KWG Max usage**			**KWG Min usage**			**KWG Max usage**		
	Velocity ($m.s^{-1}$)	Depth (m)	Shear stress ($N.m^{-2}$)	Velocity ($m.s^{-1}$)	Depth (m)	Shear stress ($N.m^{-2}$)	Velocity ($m.s^{-1}$)	Depth (m)	Shear stress ($N.m^{-2}$)	Velocity ($m.s^{-1}$)	Depth (m)	Shear stress ($N.m^{-2}$)
Baseline	**0.576**	**0.044**	**2.203**	**0.576**	**0.044**	**2.203**	**0.576**	**0.044**	**2.203**	**0.576**	**0.044**	**2.203**
ECO-Max	0.45	0.038	0.973	0.531	0.049	1.28	0.44	0.037	0.962	0.477	0.043	1.076
ECO-Min	0.38	0.032	0.761	0.451	0.039	0.994	0.382	0.032	0.766	0.45	0.039	0.992
GWR-Max	0.431	0.036	0.934	0.48	0.044	1.086	0.442	0.038	0.969	0.481	0.044	1.088
GWR-Min	0.399	0.034	0.821	0.434	0.037	0.944	0.375	0.032	0.745	0.405	0.034	0.843
RWH-Max	0.625	0.065	1.629	0.688	0.076	1.895	0.614	0.062	1.59	0.63	0.066	1.647
RWH-Min	0.548	0.053	1.334	0.58	0.057	1.455	0.579	0.057	1.452	0.586	0.058	1.482
	50%						**25%**					
	KWG Max usage			**KWG Min usage**			**KWG Max usage**			**KWG Min usage**		
	Velocity ($m.s^{-1}$)	Depth (m)	Shear stress ($N.m^{-2}$)	Velocity ($m.s^{-1}$)	Depth (m)	Shear stress ($N.m^{-2}$)	Velocity ($m.s^{-1}$)	Depth (m)	Shear stress ($N.m^{-2}$)	Velocity ($m.s^{-1}$)	Depth (m)	Shear stress ($N.m^{-2}$)
ECO-Max	0.457	0.04	1.012	0.464	0.041	1.034	0.447	0.038	0.983	0.459	0.041	1.018
ECO-Min	0.385	0.033	0.777	0.391	0.033	0.796	0.397	0.034	0.816	0.419	0.035	0.89
GWR-Max	0.412	0.035	0.868	0.47	0.042	1.052	0.412	0.035	0.867	0.434	0.037	0.944
GWR-Min	0.374	0.032	0.743	0.397	0.034	0.817	0.38	0.032	0.759	0.368	0.031	0.723
RWH-Max	0.619	0.064	1.607	0.638	0.068	1.682	0.639	0.068	1.685	0.61	0.062	1.578
RWH-Min	0.561	0.055	1.38	0.556	0.054	1.36	0.55	0.053	1.339	0.581	0.057	1.462

Table 4-6: The effect on hydraulic parameters due to the implementation of KWG at various penetration rate with water conservation strategies. The velocity, depth and shear stress values indicated in the table is the maximum achieved values in the sewer network of 160mm diameter and slope of 1:250

The maximum velocity achieved due to the implementation of ECO and GWR technologies with KWG (maximum and minimum water use) at various penetration rates was in the range of 0.37 – 0.481 m.s^{-1} at the catchment outfall of the new sewer network with pipe diameter of 160mm and slope of 1:250. The maximum velocity achieved due to the implementation of RWH with KWG (maximum and minimum water use) at various penetration rates was in the range of 0.548 – 0.688 m.s^{-1}. The maximum shear stress due to the implementation of ECO and GWR technologies with KWG (maximum and minimum water use) at various penetration rates was predicted to be in the range of 0.72 – 1.08 N.m^{-2}. The maximum shear stress due to the implementation of RWH technology with KWG (maximum and minimum water use) at various penetration rates was predicted to be in the range of 1.334 – 1.895 N.m^{-2}. The maximum depth in the sewer network due to the implementation of water conservation technologies with KWG (maximum and minimum water use) at various penetration rates was predicted to be in the range of 0.032 m – 0.076 m. The graphical representation in Appendix C-1 to Appendix C-8 shows the effect of KWG implementation at 100%, 75%, 50% and 25% penetration rate along with water conservation technologies on the hydraulic parameters in comparison to the baseline scenario at the catchment outfall of the new sewer network with pipe diameter of 160mm and slope of 1:250.

4-2-2 Pipe network of 110mm diameter and slope of 1:250

The maximum velocity, maximum depth and maximum shear stress achieved in this sewer network on implementation of KWG at various penetration rates along with 100% implementation of water conservation technologies at the catchment outfall is shown in table 4-7 in detail.

	100%						**75%**					
	KWG Min usage			**KWG Max usage**			**KWG Min usage**			**KWG Max usage**		
	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})
Baseline	**0.576**	**0.044**	**2.203**	**0.576**	**0.044**	**2.203**	**0.576**	**0.044**	**2.203**	**0.576**	**0.044**	**2.203**
ECO-Max	0.461	0.042	1.035	0.559	0.057	1.399	0.464	0.043	1.044	0.512	0.05	1.219
ECO-Min	0.408	0.036	0.853	0.474	0.045	1.073	0.408	0.036	0.852	0.473	0.045	1.07
GWR-Max	0.457	0.042	1.023	0.515	0.05	1.228	0.473	0.045	1.07	0.516	0.05	1.233
GWR-Min	0.424	0.039	0.904	0.458	0.042	1.026	0.406	0.036	0.848	0.427	0.039	0.914
RWH-Max	0.657	0.077	1.824	0.714	0.09	2.118	0.672	0.08	1.898	0.639	0.073	1.741
RWH-Min	0.58	0.062	1.478	0.611	0.067	1.614	0.613	0.068	1.621	0.607	0.066	1.597
	50%						**25%**					
	KWG Max usage			**KWG Min usage**			**KWG Max usage**			**KWG Min usage**		
	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})
ECO-Max	0.46	0.043	1.051	0.491	0.047	1.139	0.47	0.044	1.06	0.485	0.047	1.112
ECO-Min	0.412	0.037	0.865	0.418	0.038	0.883	0.418	0.038	0.884	0.442	0.04	0.969
GWR-Max	0.438	0.04	0.953	0.5	0.048	1.172	0.434	0.039	0.938	0.457	0.042	1.024
GWR-Min	0.404	0.035	0.841	0.421	0.038	0.893	0.405	0.036	0.846	0.398	0.035	0.825
RWH-Max	0.652	0.075	1.797	0.677	0.081	1.923	0.675	0.08	1.91	0.64	0.073	1.745
RWH-Min	0.595	0.064	1.542	0.59	0.064	1.522	0.586	0.063	1.506	0.612	0.067	1.617

Table 4-7: The effect on hydraulic parameters due to the implementation of KWG at various penetration rate with water conservation strategies. The velocity, depth and shear stress values indicated in the table is the maximum achieved values in the sewer network of 110mm diameter and slope of 1:250

The maximum velocity achieved due to the implementation of ECO and GWR technologies with KWG (maximum and minimum water use) at various penetration rates was in the range of 0.405 – 0.559 m.s^{-1} at the catchment outfall of the new sewer network with pipe diameter of 110mm and slope of 1:250. The maximum velocity achieved due to the implementation of

RWH with KWG (maximum and minimum water use) at various penetration rates was in the range of 0.548 – 0.688 m.s^{-1}. The maximum shear stress due to the implementation of ECO and GWR technologies with KWG (maximum and minimum water use) at various penetration rates was predicted to be in the range of 0.825 – 1.399 N.m^{-2}. The maximum shear stress due to the implementation of RWH technology with KWG (maximum and minimum water use) at various penetration rates was predicted to be in the range of 1.478 – 1.923 N.m^{-2}. The maximum depth in the sewer network due to the implementation of ECO and GWR technologies with KWG (maximum and minimum water use) at various penetration rates was predicted to be in the range of 0.035 m – 0.057 m. The maximum depth in the sewer network due to the implementation of RWH technology with KWG (maximum and minimum water use) at various penetration rates was predicted to be in the range of 0.062 m – 0.09 m. The effect of KWG implementation at 100%, 75%, 50% and 25% penetration rate along with water conservation technologies on the hydraulic parameters in comparison to the baseline scenario at the catchment outfall of the new sewer network with pipe diameter of 110mm and slope of 1:250 can be seen in the form of graphical representation in Appendix D-1 to Appendix D-8.

4-2-3 Pipe network of 110mm diameter and slope of 1:160

The maximum velocity, maximum depth and maximum shear stress achieved in this sewer network on implementation of KWG at various penetration rates along with water conservation technologies is shown in table 4-8 in detail.

	100%						**75%**					
	KWG Min usage			**KWG Max usage**			**KWG Min usage**			**KWG Max usage**		
	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})
Baseline	**0.576**	**0.044**	**2.203**	**0.576**	**0.044**	**2.203**	**0.576**	**0.044**	**2.203**	**0.576**	**0.044**	**2.203**
ECO-Max	0.512	0.039	1.297	0.608	0.054	1.672	0.518	0.04	1.326	0.561	0.046	1.48
ECO-Min	0.463	0.033	1.118	0.534	0.041	1.39	0.462	0.033	1.115	0.533	0.041	1.387
GWR-Max	0.565	0.047	1.5	0.565	0.047	1.5	0.518	0.04	1.323	0.568	0.047	1.514
GWR-Min	0.504	0.039	1.264	0.506	0.039	1.272	0.46	0.033	1.108	0.477	0.036	1.16
RWH-Max	0.714	0.071	2.167	0.77	0.084	2.469	0.691	0.068	2.049	0.729	0.074	2.244
RWH-Min	0.641	0.057	1.827	0.664	0.063	1.923	0.657	0.062	1.888	0.668	0.063	1.943
	50%						**25%**					
	KWG Max usage			**KWG Min usage**			**KWG Max usage**			**KWG Min usage**		
	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})	Velocity (m.s^{-1})	Depth (m)	Shear stress (N.m^{-2})
ECO-Max	0.52	0.042	1.383	0.543	0.044	1.411	0.529	0.041	1.372	0.54	0.043	1.406
ECO-Min	0.467	0.034	1.131	0.471	0.035	1.144	0.471	0.035	1.146	0.486	0.037	1.192
GWR-Max	0.483	0.037	1.179	0.547	0.045	1.425	0.48	0.036	1.171	0.504	0.039	1.264
GWR-Min	0.456	0.033	1.094	0.473	0.035	1.15	0.459	0.033	1.105	0.446	0.032	1.055
RWH-Max	0.703	0.07	2.109	0.73	0.075	2.25	0.73	0.074	2.248	0.691	0.068	2.05
RWH-Min	0.646	0.06	1.844	0.645	0.059	1.839	0.388	0.059	1.835	0.665	0.063	1.929

Table 4-8: The effect on hydraulic parameters due to the implementation of KWG at various penetration rate with water conservation strategies. The velocity, depth and shear stress values indicated in the table is the maximum achieved values in the sewer network of 110mm diameter and slope of 1:160

The maximum velocity achieved due to the implementation of ECO and GWR technologies with KWG (maximum and minimum water use) at various penetration rates was in the range of 0.446–0.608 m.s^{-1} at the catchment outfall of the new sewer network with pipe diameter of 110mm and slope of 1:160. The maximum velocity achieved due to the implementation of RWH with KWG (maximum and minimum water use) at various penetration rates was in the range of 0.641–0.77 $m.s^{-1}$. The maximum shear stress due to the implementation of water conservation technologies with KWG (maximum and minimum water use) at various penetration rates was predicted to be in the range of 1.055–2.469 $N.m^{-2}$. The maximum depth in the sewer network due to the implementation of water conservation technologies with KWG (maximum and minimum water use) at various penetration rates was predicted to be in the range of 0.033–0.084 m. The graphical representation in Appendix E-1 to Appendix E-8 shows the graphical representation of the effect of KWG implementation at 100%, 75%, 50% and 25% penetration rate along with water conservation technologies on the hydraulic parameters in comparison to the baseline scenario at the catchment outfall.

Chapter 5

Discussion

5-1 Developed stochastic sewer model

The methodology developed to analyse the effect of implementation of KWG at various penetration rates along with water conservation strategies on sewer system did not previously exist. The stochastic discharge pattern from KWG was developed using SIMDEUM®. It is a tool developed to generate stochastic water demand and discharge patterns for residential and non-residential buildings [47]. The model requires several inputs such as user data, which includes household size, age, gender and occupation and individual appliance specifications. A maximum and minimum bound of future household occupancy was used to generate the model illustrating the effect of urbanisation and increase of single occupancy households in urban localities. SIMDEUM WW® was used to generate appliance specific discharge patterns for wastewater flow and concentrations. The addition of KWG in SIMDEUM® and SIMDEUM WW® to generate stochastic demand and discharge patterns was successful with the data obtained on KWG specifications. This model was integrated with infoWorks ICM® to predict the effect on hydraulic and quality parameters in the sewers due to the implementation of KWG with water conservation technologies. Recently a paper was published on the prediction of flow, nutrient and temperature changes in a sewer under water conservation scenario by Bailey, et al.[50]. Their work focused on validation of SIMDUEM WW® and predicting the mass load of nutrients and and hydraulic parameters in the sewer system. Recommendations from this work could not be adopted since there was no access to the new release of InfoWorks ICM® with the detection of time varying suspended solids entry to the sewer system during the start of this research. Thus the sediment transport was not modelled in this thesis.

5-2 Impacts on existing sewer system

5-2-1 Hydraulic modelling

The effect of application of KWG (maximum and minimum usage) at different penetration rates along with various future water saving scenarios such as ECO (maximum and minimum occupancy), GWR (maximum and minimum occupancy) RWH (maximum and minimum occupancy) on the hydraulic parameters were analysed using stochastic flow and wastewater quality model on a small neighbourhood.

Various researchers have showed that reduction in water demand and reuse of domestic wastewater will change the characteristics of sewage. These changes include reduction in peak-time flow up to 80% [49], wastewater failing to achieve the self cleansing velocity of 0.6 – 1.0 $m.s^{-1}$ [3] and increase in nutrient mass loading [50]. A similar observation can be made from the current study with KWG effluent being discharged in to the sewers along with water conservation technologies. It can be observed from table 4-1 to table 4-5 that the implementation of ECO and GWR with KWG will significantly reduce the wastewater flow in the sewers up to 6% – 54%. This reduction is due to the application of efficient showers, smart taps, low volume WC flushes and waterless washing machines and dishwashers. However the variability of flow due to the implementation of KWG at 100% penetration rate with ECO and GWR is high as compared to the implementation of KWG at 25% penetration rate with ECO and GWR. Thus it can be said that as penetration rate of KWG decreases the variability of diurnal flow pattern decreases. This is because of less number of household using KWG leading to lower flush volumes and shorter duration as penetration rate decreases. It was predicted that the implementation of ECO and GWR technologies with KWG will significantly lower the morning peaks in the sewers. The published work of Ellis et al, also concluded that low water use practices and urban lifestyle will lead to flat daily wastewater profiles [55]. Thus, from a design perspective, the reduction in flow rates and transition in diurnal wastewater flow patterns will allow the possibility to postpone the enlargement of existing sewer systems, to construct new sewers of smaller pipe diameter and lower energy consumption for sewage pumping. The implementation of KWG with RWH scenario showcases daily flowrate patterns very similar to the baseline scenario as the scenario just utilises non potable water instead of potable water for toilet flushing and washing machines.

The quantitative effect of KWG application along with water conservation strategies on the shear stress in sewer lines at the catchment outfall is shown in table 4-1, 4-3, 4-4 and 4-5. The shear stress for 100%, 75%, 50%, and 25% penetration rates of KWG with water conservation technologies was predicted to be in the range of 0.24–0.44 $N.m^{-2}$, 0.23–0.38 $N.m^{-2}$, 0.24–0.38 $N.m^{-2}$ and 0.23–0.39 $N.m^{-2}$ respectively. It can be observed that there is dramatic reduction of 40-71%, 48-72%, 54-71% and 54-72% in shear stress values when compared to the baseline scenario for water conservation technologies along with KWG at 100%, 75%, 50%, and 25% penetration rates respectively. This shows that the addition of solids (1-6mm diameter) due to application of KWG along with water conservation scenario in the current sewer system may struggle to transport solids. This is substantiated by the study conducted by Penn, et al.[3] which states that the critical shear that needs to be achieved to transport solids of diameter of 1-6mm should be 0.8-1.42 $N.m^{-2}$.

The velocity in the existing sewer has reduced by half because of the implementation of ECO and GWR technology with KWG as compared to the baseline scenario and reduced up to one fourth for RWH with KWG scenario as shown in table 4-1, 4-3, 4-4 and 4-5. The results show that the maximum velocity achieved for 100%, 75%, 50% and 25% penetration rate of KWG with ECO, GWR and RWH scenario was observed to be 0.45 $m.s^{-1}$, 0.39 $m.s^{-1}$, 0.35 $m.s^{-1}$, and 0.32 $m.s^{-1}$ respectively. It can be observed that there is drop in flow velocity below the critical velocity of 0.5-1.0 $m.s^{-1}$ at the catchment outfall due to the implementation of KWG with water conservation strategy. Thus the implementation of water conservation technologies along with KWG has resulted in concentrated flow which leads to low velocity of wastewater as compared to the baseline scenario. This could potentially lead to blockages in the current sewer system. These findings are similar to the findings of study conducted by Bailey, et al.[50] on the impact of usage of smart water appliances, water reuse and recycle in an urban residential locality.

5-2-2 Quality modelling

COD, TKN and TPH are the major nutrients to be assessed in the wastewater for resource recovery options at a treatment location [19]. Visual inspection of the cumulative frequency graphs of COD, TKN ans TPH concentration in wastewater at the catchment outfall from Appendix B-1(d-f) to Appendix B-8(d-f) show that the population change (max.occupancy and min.occupancy scenario) has negligible impact on the wastewater quality modelling. The nutrient loading per person per day due to implementation of KWG at various penetration rates along with water conservation strategies at the catchment outfall is predicted to be in the range of 59.5–194.63 g COD, 4.76–14.48 g TKN and 0.38–1.45 g TPH as shown in table 4-2. The nutrient loading obtained in the current study is similar to the daily per capita loading range of 86-137 g COD, 8-15 g TKN and 1-3 g TPH found in various similar studies [50] [51] [11]. The increase in COD mass load values in the current research is because of the addition of KWG (high organic content) along with water conservation technologies. However, this difference in mass load of COD aligns with the values separately published by researchers on ground kitchen waste [36] [40] [16] [52] [53]. The mass load of TPH values is lower than the values found in previous researches. This might be due to the application of low phosphate detergents incorporated in this study model.

It was also found that the addition of KWG with GWR will prove to be the most beneficial option for resource recovery of nutrients as this scenario provides a small operating range. This will be an advantage for design of decentralised treatment and recovery system. By having a decentralised treatment system with non-corrosive sewer lines, a short retention time of slurry in the sewers can be achieved avoiding negative issues such as (H_2S) generation and potential decay of organics in the sewers [61]. A very similar conclusion was drawn from the study of Zeeman et al, 2011 [70] which states that diversion of GW and addition of black water (BW) with kitchen waste can separate up to 80-92% of nutrients. The average nutrient load in black water is found to be 61 g COD, 9.8 g TKN and 1.3 g TPH per capita per day [71]. The anaerobic treatment of BW using UASB reactor can yield up to 10 L CH_4 $p^{-1}d^{-1}$ [70] and 0.22kg P $p^{-1}d^{-1}$ via struvite precipitation[7]. Since the mass load of nutrients obtained in this study with addition of KWG effluent is in the range of 59.5–194.63 g COD, 4.76–14.48 g TKN and 0.38–1.45 g TPH which significantly high compared to the mass load of BW, the resource recovery expectancy can be high. The implementation of KWG with RWH will not provide significant increase in nutrient loading as compared to the baseline scenario since RWH scenario will just replace the potable water with non-portable alternatives for toilet flushing and washing machine.

As expected it was observed that as the penetration rate of KWG decreases the range of nutrient loading decreases. Apart from this it can also be seen that in all the penetration rates of KWG minimum usage of KWG will produce more narrower range of nutrients. Most often this can be linked to flow reduction and limited dilution due to low frequency of usage of KWG.

5-3 Impact on new sewer system

According to the literature review conducted and the results as discussed in section 5-2-1, it is evident that the traditional sewerage system designed for system peaks with diurnal flow patterns does not comply in transporting flow with flatter daily profile. Hence a new sewer design is necessary to transport concentrated domestic wastewater without sedimentation and clogging. The same conclusion was drawn from a similar study conducted by Bailey et al., 2020 [50] with low flow-high nutrient load wastewater. In order to achieve this, six future scenario were simulated to investigate the effect of addition of KWG along with water conservation technologies on hydraulic parameters. The stochastic flow and wastewater model was investigated for a new sewer network with a PVC network with pipe diameter of 160mm and a slope of 1:250, 110mm and a slope of 1:250 and 110mm diameter and slope of 1:160. Apart from the hydraulic modeling, the wastewater quality was also observed and no significant difference was noticed due to change in network as compared to the existing system as discussed in section 5-2-2.

5-3-1 Pipe network of 160mm diameter and slope of 1:250

The maximum velocity achieved at the catchment outfall of the new network with pipe diameter of 160mm and slope of 1:250 for implementation of KWG (maximum and minimum usage) with water conservation technologies can be seen in table 4-6. It can be observed that the maximum velocity of wastewater flow for implementation of KWG (maximum and minimum usage) with ECO and GWR scenario at all the penetration rates is in the range of 0.37–0.481 $m.s^{-1}$ which is insufficient to achieve the self cleansing velocity of 0.5-1 $m.s^{-1}$ for solids movement as published in work of Penn et al, 2013 [3] and supported by the work of Kegebein et al, 2001, Bolzonella et al, 2003 and Evans et al, 2010 [15] [40] [44]. The maximum velocity of wastewater flow for implementation of KWG (maximum and minimum usage) with RWH scenario at all the penetration rates is in the range of 0.548–0.688 $m.s^{-1}$ which is just sufficient enough to achieve the self cleansing velocity. Thus the network needs optimization to transport wastewater from KWG effluent with ECO and GWR technologies. This was carried out by further reducing the diameter of the pipe network to 110mm.

The graphical representation from Appendix C-1a to Appendix C-8a show the effect of KWG implementation along with water conservation strategies on the wastewater flow rate at the catchment outfall of the new network with pipe diameter of 160mm and slope of 1:250. It can be observed that the flowrate is low for implementation of KWG with ECO and GWR scenario, however, diurnal pattern can be observed for maximum usage of KWG at all the penetration rates. This can be attributed to the high water consumption of KWG and smaller pipe diameters with increased gradient. This proves that the pipe capacity is utilised throughput the day. Although flatter profiles of flow can be observed for minimum usage of KWG with ECO and GWR strategies at all penetration rates which can be attributed to lower water discharge from KWG leading to less flowrate.

5-3-2 Pipe network of 110mm diameter and slope of 1:250

The maximum velocity achieved at the catchment outfall of the new network with pipe diameter of 110mm and slope of 1:250 for implementation of KWG (maximum and minimum usage) with water conservation technologies can be seen in table 4-7. It can be observed that the maximum velocity of wastewater flow for implementation of KWG (minimum usage) with ECO and GWR scenario at all the penetration rates is in the range of 0.405–0.47 m.s^{-1} which is still insufficient to achieve the self cleansing velocity of 0.5-1 m.s^{-1} for solids movement as published by various researchers [3] [15] [40] [44]. Also it can be observed that the maximum velocity of wastewater flow for implementation of KWG (maximum usage) with ECO and GWR scenario at all the penetration rates is in the range of 0.398–0.559 m.s^{-1}. Thus it was predicted that the self cleansing velocity can be achieved for 100% and 75% penetration rate of KWG (maximum usage; a flow of 0.40 L.s^{-1} and flush duration of 72 seconds) with water conservation technologies for maximum household occupancy.

It can also be observed from table 4-7 that in all the scenarios the maximum depth of wastewater in the pipe is below 0.088m except for the scenario of 100% implementation of KWG (maximum usage) with RWH (maximum occupancy). The maximum depth of flow for 100% implementation of KWG (maximum usage) with RWH (maximum occupancy) was observed to be 0.09. This does not satisfy the design criteria for safely transporting wastewater which states that maximum depth of flow in design shall be limited to 80% of the diameter of the pipe at peak flow and can lead to damage of pipes [41].

The effect of KWG implementation along with water conservation strategies on the wastewater flow rate at the catchment outfall of the new network with pipe diameter of 110mm and slope of 1:250 is shown graphically from Appendix D-1a to Appendix D-8a. It can be observed that there is no significant difference in the flowrate patterns between this scenario and the network with PVC pipe of 160mm diameter and 1:250 slope.

5-3-3 Pipe network of 110mm diameter and slope of 1:160

The maximum velocity of wastewater for 100% and 75% implementation of KWG (maximum and minimum usage) with ECO (maximum occupancy) and GWR scenario for the network with PVC pipe of 110mm diameter and 1:160 slope was predicted to be in the range of 0.504–0.608 m.s^{-1} which is just sufficient to achieve the self cleansing velocity of 0.5-1 m.s^{-1} as shown in table 4-8. However, there can still be chances of clogging and sedimentation in the case of 50% and 25% implementation of KWG (maximum and minimum usage) with ECO and GWR scenario at minimum occupancy. A similar assessment of the impact of GWR and water efficient technologies was made by Penn et al., 2013 where they concluded that 33% of implementation of these technologies might tend of have issues of blockages in street scale pipes of 150mm diameter. It can be observed that in all the scenarios the depth of wastewater in the pipe is below 0.088m satisfying the design criteria of 0.8 times the diameter of the pipe during peak flow [41].

The graphical representation from Appendix E-1a to Appendix E-8a show the effect of KWG implementation along with water conservation strategies on the wastewater flow rate at the catchment outfall of the new network with pipe diameter of 110mm and slope of 1:160. By visual inspection it can be observed that there is no significant difference in the flowrate patterns between this scenario and the network with PVC pipe of 110mm diameter with a slope of 1:250 slope.

5-4 Realization of addition of KWG with water conservation technologies

Traditional sewers are generally constructed with a design life of 50 years [72]. Currently all the Dutch households are connected to sewerage system. Considering these two facts and based on the discussions on the impact of the application of KWG with water conservation technologies on the sewer network in the previous sections it might not be realistic to completely change the sewer network and adopt a new sewer design in big cities with established sewerage network connected to centralized wastewater treatment facilities. However, the installation of KWG and water conservation technologies in households can be realized in a newly developed area.

The concept of new sanitation, resource recovery and reuse is gaining spotlight worldwide. The important aspect of this concept is the reduction of mixing and dilution of waste which can be achieved through separation at source [73]. The full scale study (32 households) of Decentralised sanitation and reuse (DeSaR) project, in Sneek, The Netherlands show that the the separate collection of black water (BW), transport via vacuum system and anaerobic digestion followed by struvite precipitation will aid in efficient recovery of energy and nutrients [70]. The pilot scale study conducted by K. Kujawa-Roeleveld et al, show that the co-digestion of concentrated black water and effluent from kitchen waste grinder in an accumulation anaerobic digester gives promising results in a DeSaR concept with biogas yield of 26.5 L capita^{-1}day^{-1} to 50.8 L capita^{-1}day^{-1} [74]. Based on the mass load of nutrients obtained in this study due to the application of KWG with ECO and GWR scenario (table 4-2) it can be said that co-digestion of KWG with source separated wastewater in a decentralised treatment plant with anaerobic digester might be a feasible solution to achieve efficient resource recovery.

Apart from economical and technical constraints, the acceptance or behaviour of people can be of concern. The usage of KWGs started in the 1930s with the USA being one of the largest users with penetration of more than 60% in households by 2019 [33]. Installations in the EU member states is relatively low (around 5% penetration). It might take several years or even decades to achieve high penetration. As observed in the current research, low penetration rates of KWG with 100% implementation of water conservation strategies will encounter insufficient self cleansing capacity which might lead to issues of clogging and sedimentation even with the new sewer design principles. The issues associated with low penetration rates and clogging in the sewer due to the application of concentrated wastewater can be resolved by the application of vacuum sewerage system [75]. Growing environmental awareness and the drive towards sustainable development goals can be of advantage in the faster absorbance of new sanitation systems in the urban household. On the other hand, further research is necessary on environmental, economic and operational benefits of the implementation of KWG with water conservation strategies.

Chapter 6

Conclusions

The results from this research indicate the following findings:

1. The addition of KWG along with water smart water appliances and greywater reuse will increase the nutrient loading in the sewerage system. The mass loading of COD, TKN and TPH was observed to increase up to 118%, 84% and 90% respectively as compared to the baseline/current scenario.

2. The dramatic reduction in diurnal peak is a result of the smart water appliances and greywater reuse. The reduction becomes less through the implementation of KWG: the higher the penetration, the less this reduction is (due to the use of water by the KWG). The reduction in flow, velocity and shear stress was observed to be 54%, 49% and 72% respectively in the current sewer network in the case study area. Whereas, implementation of KWG with RWH shows similar hydraulic results as the baseline case. However, this reduction in flow, velocity and shear stress might lead to issues of clogging and sedimentation in the contemporary sewers. This asserts the need to design pipes with smaller diameter and steeper slopes.

3. The results from the investigation of new sewer design show that 100% and 75% implementation of KWG with water conservation technologies will achieve self cleansing capacity which will prevent clogging and sedimentation for a piping network of 110mm diameter at a slope of 1:160. Lower market penetration of KWG along with water conservation strategies with new sewer principles might still face issues of sedimentation and clogging with insufficient self cleansing capacity. Thus it can be concluded that the negative impact due to the addition of KWG effluent along with water conservation strategies on the sewer system can be tackled by efficient design with smaller pipe diameter, steeper slopes and high penetration rate of KWG installations.

4. In order to arrive at the above mentioned conclusions a new stochastic sewer model was developed. The up-gradation of SIMDEUM® and SIMDEUM WW® with kitchen waste grinder along with water conservation strategies in a residential building to generate stochastic demand and discharge patterns was successful.

Eventually, this research has demonstrated that application of both KWG along with water conservation strategies at higher penetration rates with efficient design of wastewater collection, transport and decentralised treatment system may aid in resource recovery and lower freshwater demand in newly developed localities.

Chapter 7

Recommendations

Some of the recommendations based on the thesis results are as follows:

1. To better understand the implication of the addition of KWG effluent along with water conservation technologies on the sewer system further studies could be addressed in comparison to the predicted hydraulic and quality parameters with field measurements. This will be a very important step in validating the developed model.
2. The upgrading of SIMDEUM® based on KWG usage behaviour of people for a large set of population and validating the predicted results with field measurements can be an improvement towards the accuracy of model prediction
3. The literature review on the concentration of resources in different KWG streams in residential areas reveals that a significant amount of solids is added into the sewers. Thus, it will be necessary to model sediment transport. It is also interesting to analyse the temperature of wastewater and thermal recovery options due to the addition of KWG effluent along with water conservation strategies.
4. In order to make the research more pragmatic for the current situation it is necessary to analyse the impact of the implementation of both water conservation strategies with KWG at low penetration rates (5%-20%).
5. Apart from the reduction in pipe diameters and increase in slope, the negative impact associated with decomposition of KWG slurry due to long retention times in the sewers may be solved by adopting a decentralised treatment and recovery with the use of a vacuum system. Thus decentralised treatment and reuse need to be considered as a pre-condition for the adaption of low water demand appliance along with KWG application. The addition of KWG along with GWR will prove to be the most beneficial option for resource recovery of nutrients as this scenario provides a small operating range. This will be an advantage for the design of decentralised treatment and recovery system. Further research is necessary to assess the feasibility of decentralised resource recovery and the vacuum system approach.

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Appendix A

Appendix-1

A-1 Water demand and nutrient mass load for urban household appliances and reuse technologies

Appliance	Demand fulfilment (lpcd)			Effluent g use^{-1}			Discharge temperature (^{o}C)	Source
	Tap water	GW	RW	COD	TKN	TPH		
Shower	52.9	-	-	12.6	0.49	0.00	35	[19] [50]
Bathroom tap	4.9	-	-	1.48	0.04	0.00	40	[19] [50]
Kitchen tap	8.1	-	-	7.48	0.35	0.03	40	[19] [50]
Dishwasher	1.2	-	-	30.00	1.35	0.00	35	[19] [50] [3]
Washing machine	10.3	-	-	65.25	0.68	0.00	35–45	[19] [50] [3]
with GWR	-	10.3	-	69.40	0.78	0.00		
with RWH	-	-	10.3	66.29	0.86	0.00		
Toilet	29.7	-	-	11.22	1.99	0.22	20	[19] [50] [3]
with GWR	-	29.7	-	11.48	2.00	0.22		
with RWH	-	-	29.7	11.28	2.00	0.22		

Table A-1: Water demand and mass load of organics and nutrients for different household appliances adapted from Bailey et al, 2020

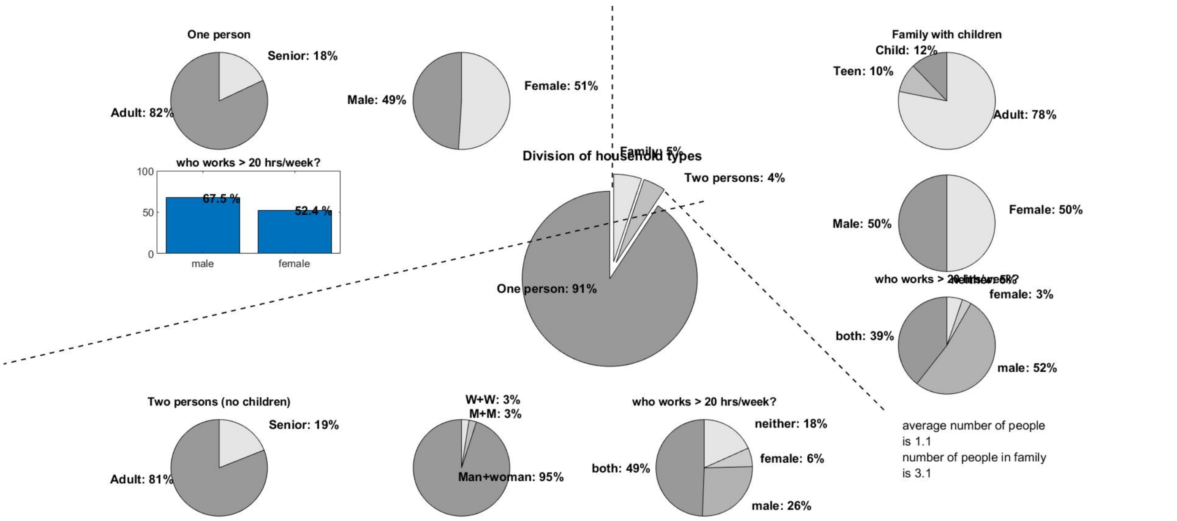
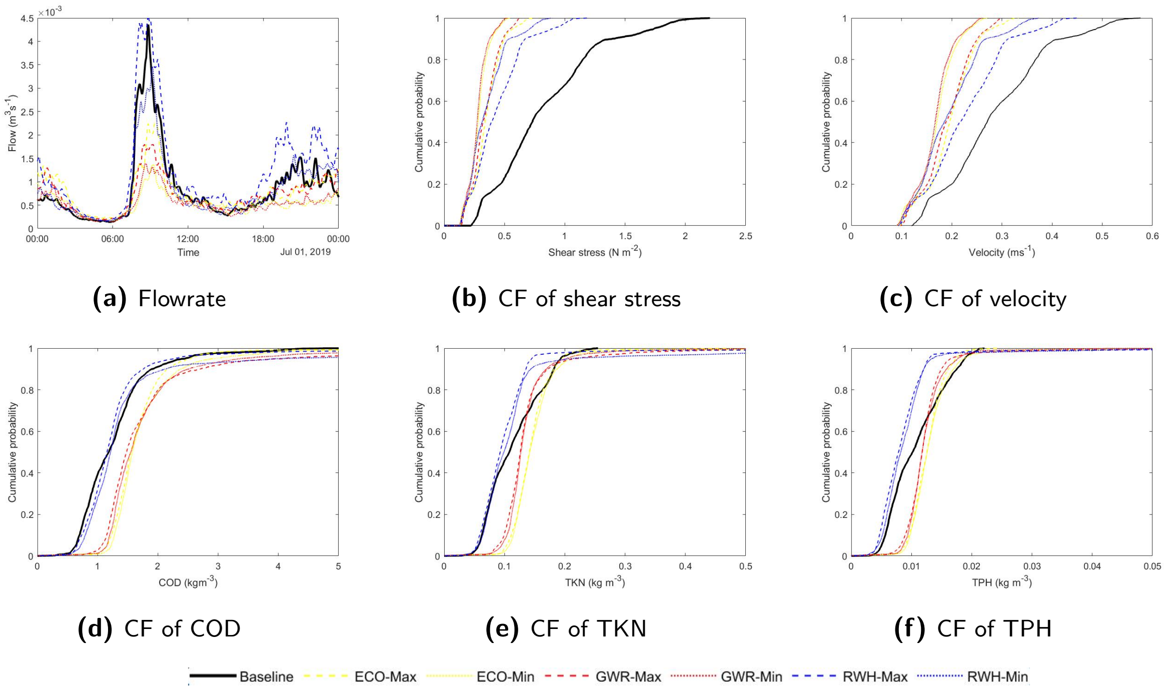


Figure A-1: Future household statistics used in SIMDEUM®

Appendix B

Appendix-2

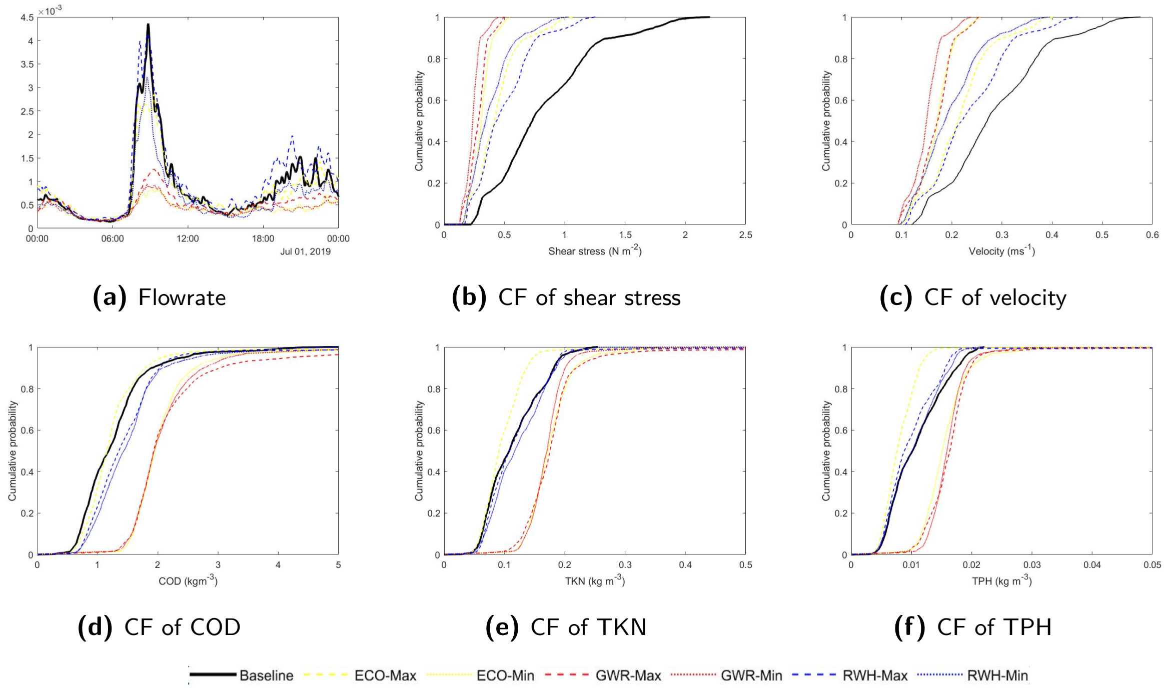
B-1 Existing sewer design



(a) Flowrate **(b)** CF of shear stress **(c)** CF of velocity

(d) CF of COD **(e)** CF of TKN **(f)** CF of TPH

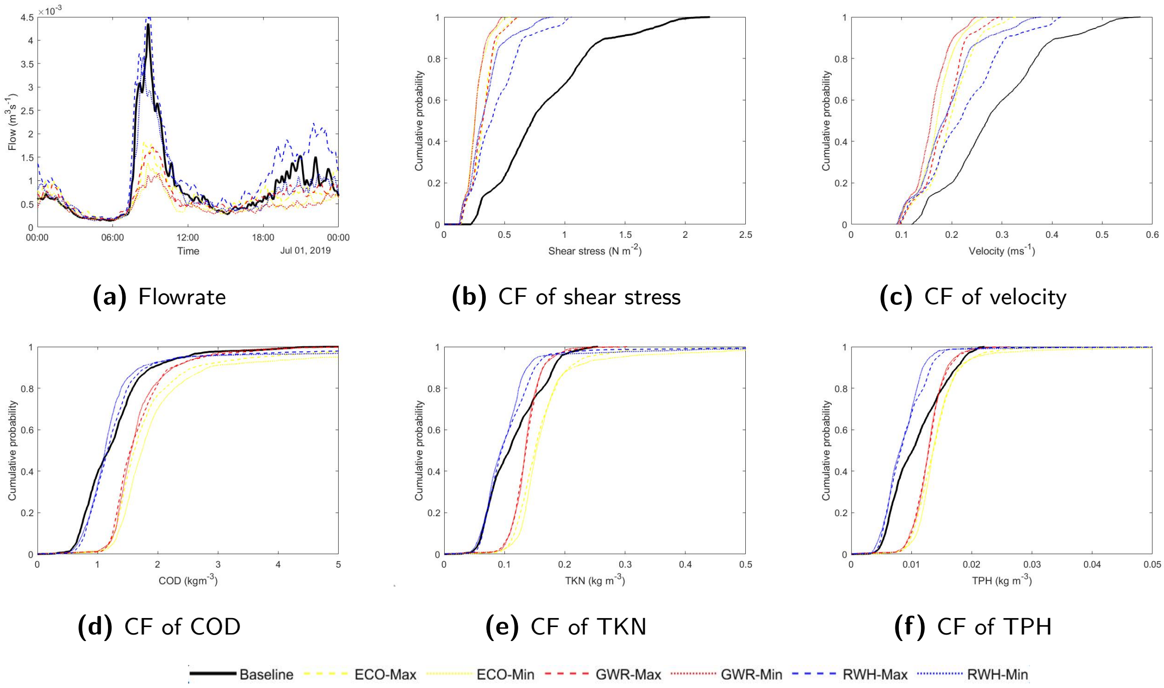
Figure B-1: Effect on hydraulic and quality parameters due to the maximum usage of KWG at 100% market penetration rate for the existing sewer system



(a) Flowrate **(b)** CF of shear stress **(c)** CF of velocity

(d) CF of COD **(e)** CF of TKN **(f)** CF of TPH

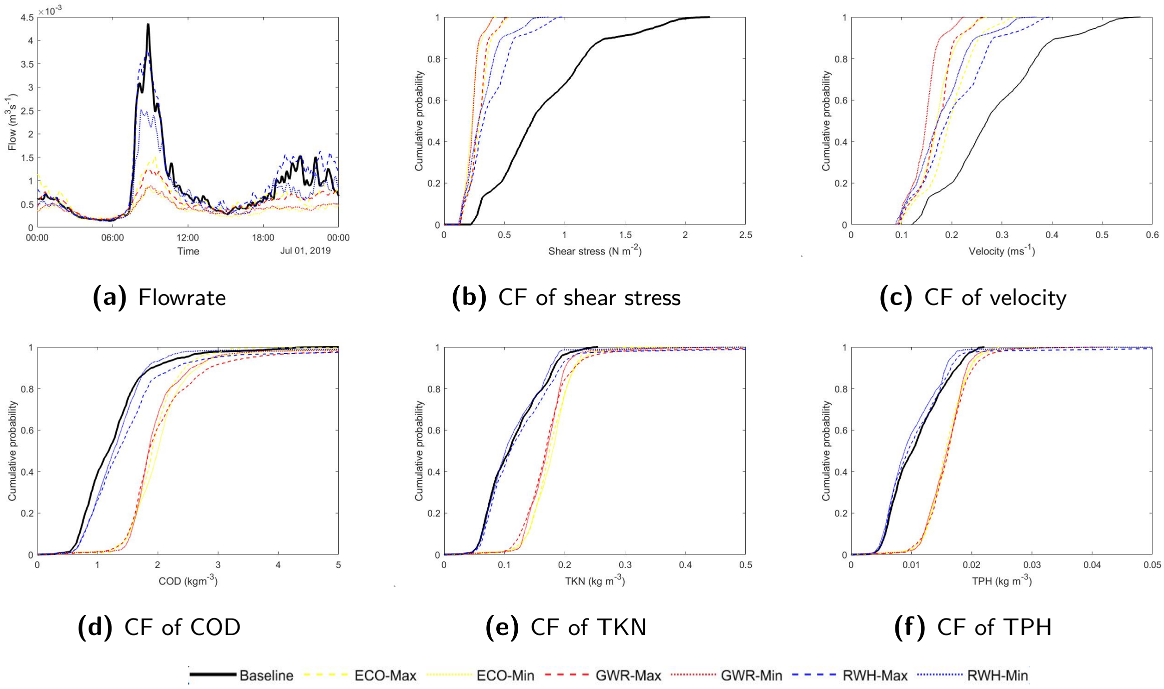
Figure B-2: Effect on hydraulic and quality parameters due to the minimum usage of KWG at 100% penetration rate for the existing sewer system



(a) Flowrate **(b)** CF of shear stress **(c)** CF of velocity

(d) CF of COD **(e)** CF of TKN **(f)** CF of TPH

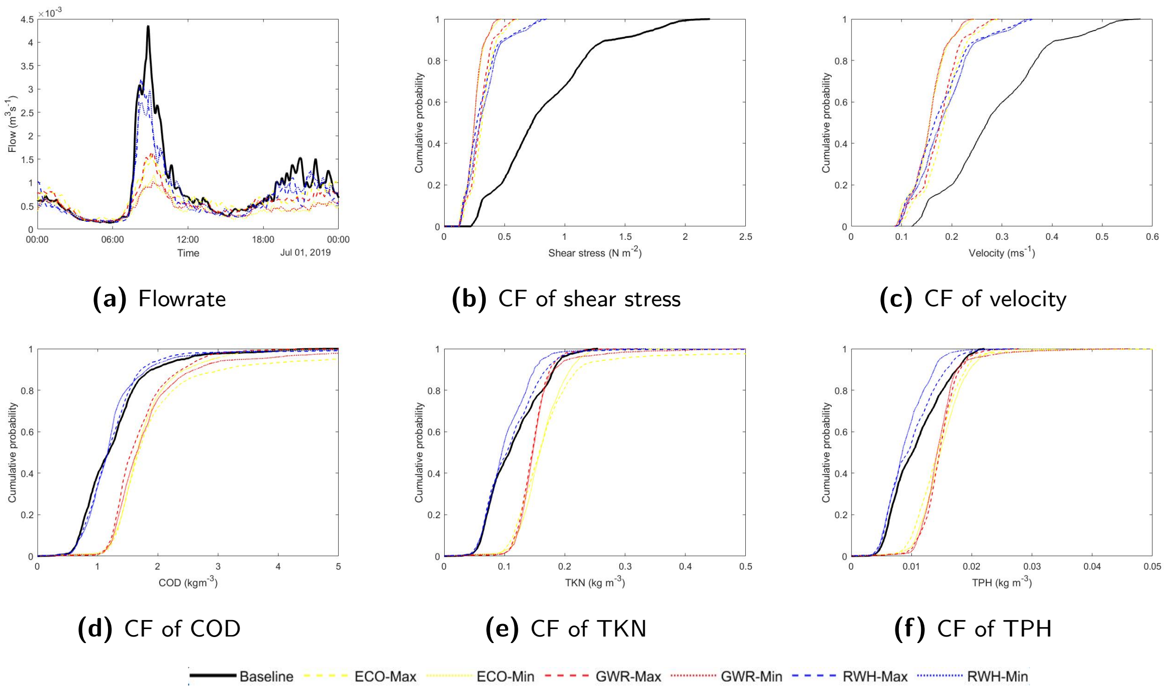
Figure B-3: Effect on hydraulic and quality parameters due to the maximum usage of KWG at 75% market penetration rate for the existing sewer system



(a) Flowrate **(b)** CF of shear stress **(c)** CF of velocity

(d) CF of COD **(e)** CF of TKN **(f)** CF of TPH

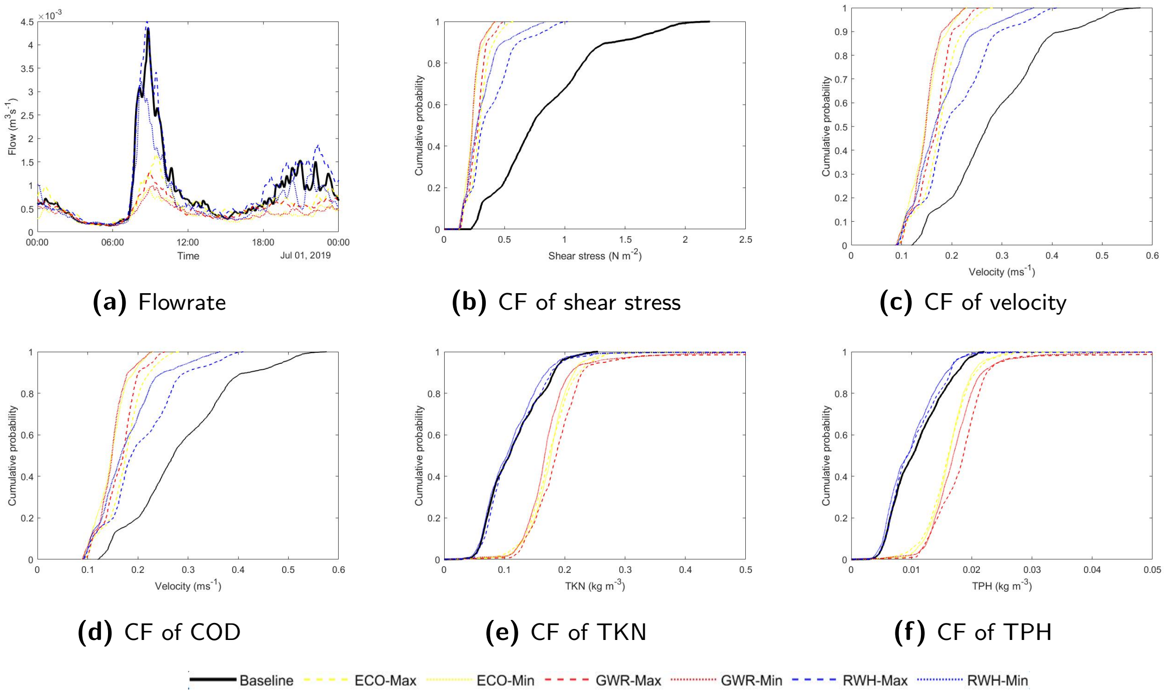
Figure B-4: Effect on hydraulic and quality parameters due to the minimum usage of KWG at 75% penetration rate for the existing sewer system



(a) Flowrate **(b)** CF of shear stress **(c)** CF of velocity

(d) CF of COD **(e)** CF of TKN **(f)** CF of TPH

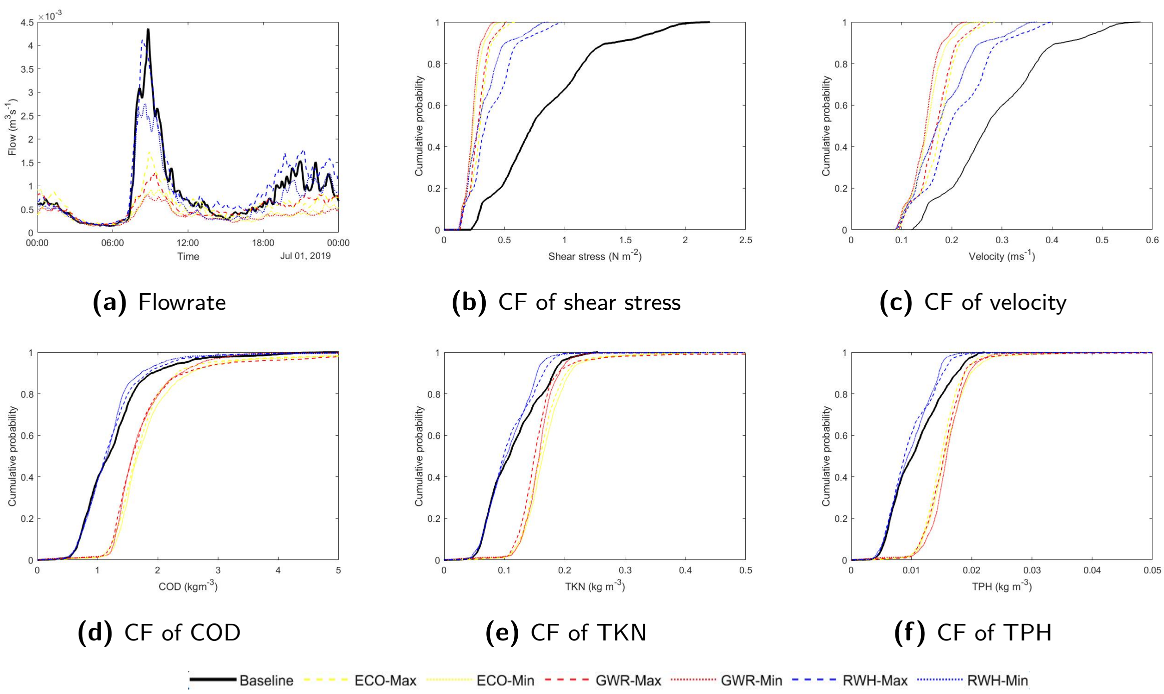
Figure B-5: Effect on hydraulic and quality parameters due to the maximum usage of KWG at 50% market penetration rate for the existing sewer system



(a) Flowrate **(b)** CF of shear stress **(c)** CF of velocity

(d) CF of COD **(e)** CF of TKN **(f)** CF of TPH

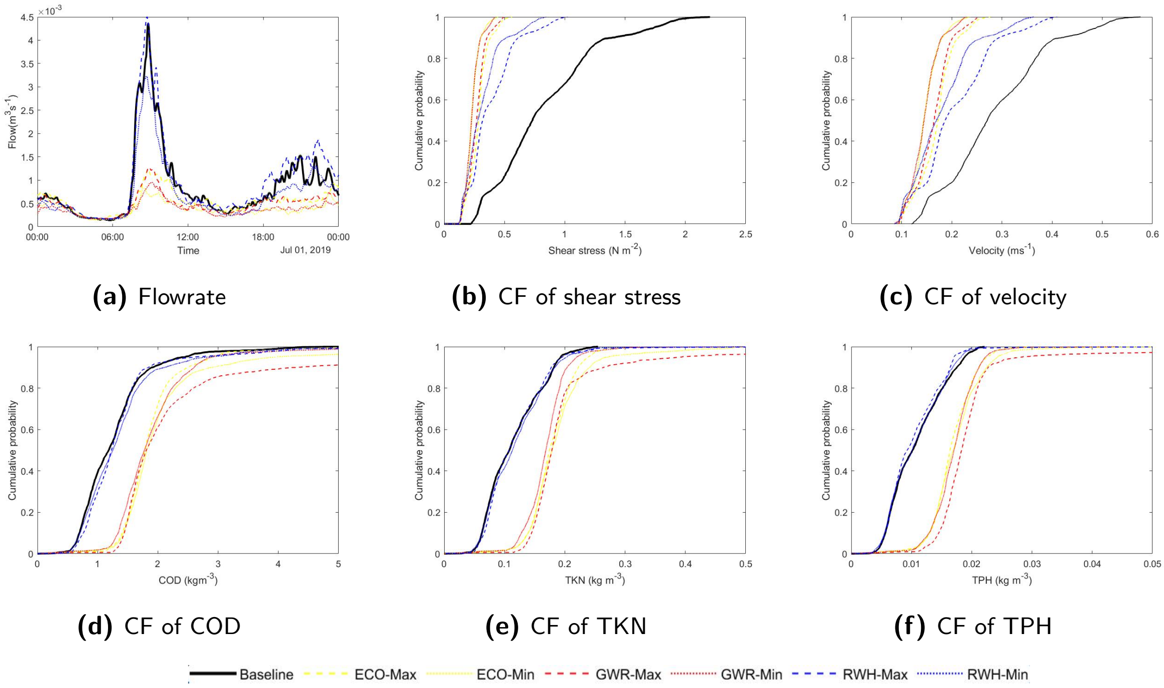
Figure B-6: Effect on hydraulic and quality parameters due to the minimum usage of KWG at 50% penetration rate for the existing sewer system



(a) Flowrate **(b)** CF of shear stress **(c)** CF of velocity

(d) CF of COD **(e)** CF of TKN **(f)** CF of TPH

Figure B-7: Effect on hydraulic and quality parameters due to the maximum usage of KWG at 25% market penetration rate for the existing sewer system



(a) Flowrate

(b) CF of shear stress

(c) CF of velocity

(d) CF of COD

(e) CF of TKN

(f) CF of TPH

Figure B-8: Effect on hydraulic and quality parameters due to the minimum usage of KWG at 25% penetration rate for the existing sewer system

Appendix C

Appendix-3

C-1 New sewer design: 160mm diameter and 1:250 slope

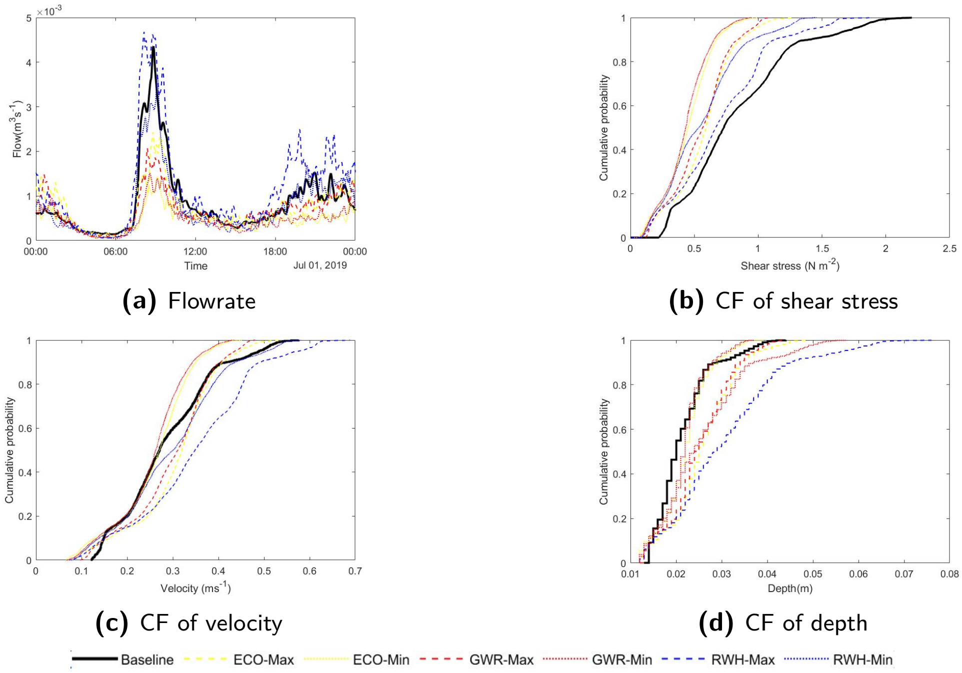


Figure C-1: Effect on hydraulic parameters due to the maximum usage of KWG at 100% market penetration rate for the pipe network of 160mm diameter and slope of 1:250

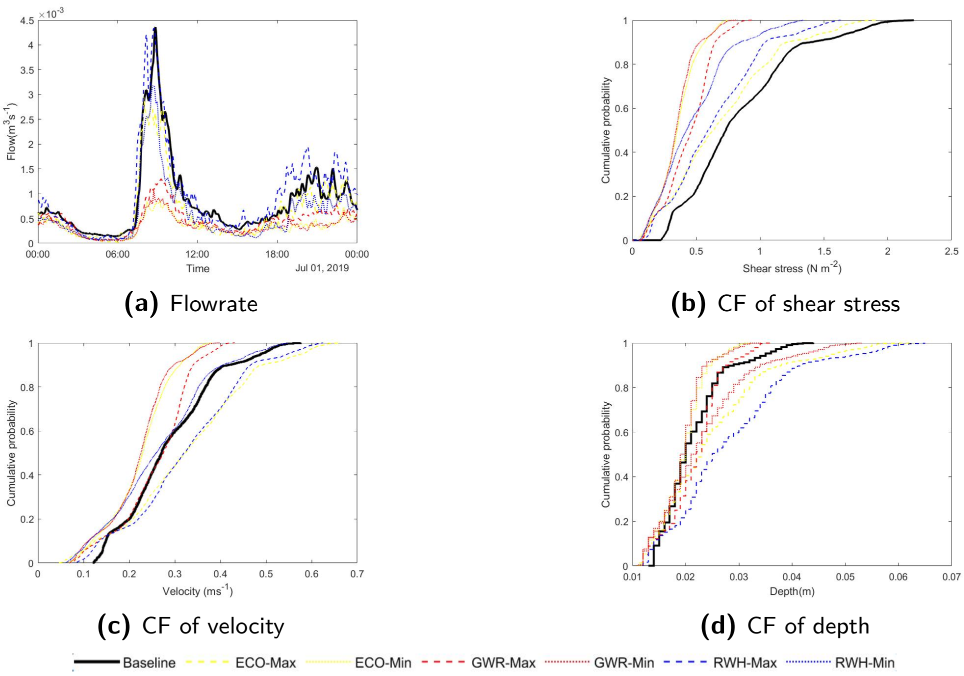
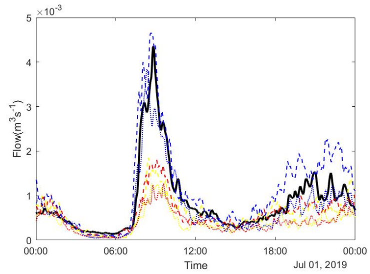
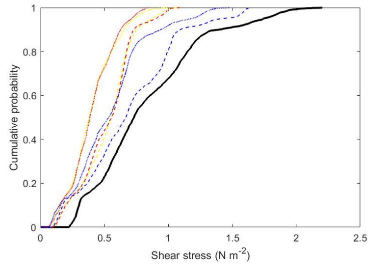


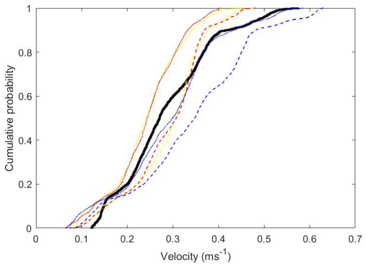
Figure C-2: Effect on hydraulic parameters due to the minimum usage of KWG at 100% market penetration rate for the pipe network of 160mm diameter and slope of 1:250



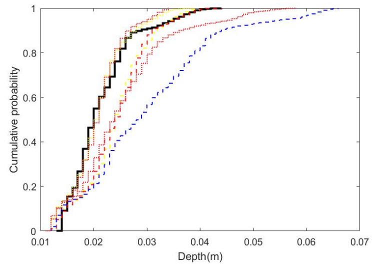
(a) Flowrate



(b) CF of shear stress

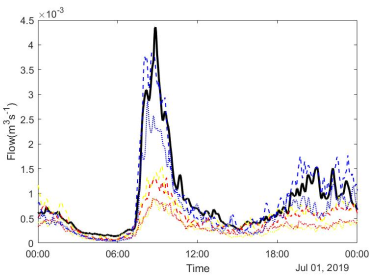


(c) CF of velocity

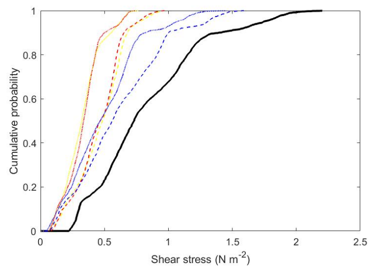


(d) CF of depth

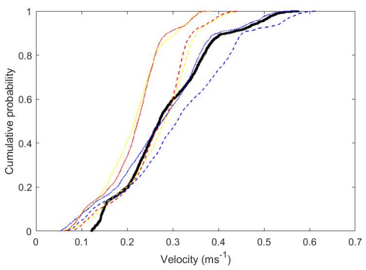
Figure C-3: Effect on hydraulic parameters due to the maximum usage of KWG at 75% market penetration rate for the pipe network of 160mm diameter and slope of 1:250



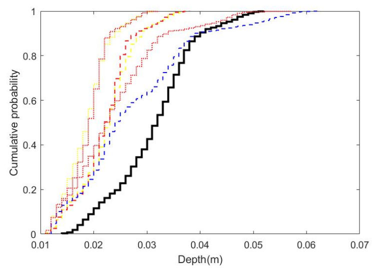
(a) Flowrate



(b) CF of shear stress

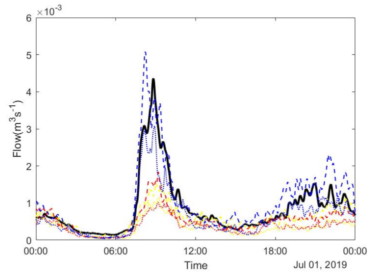


(c) CF of velocity

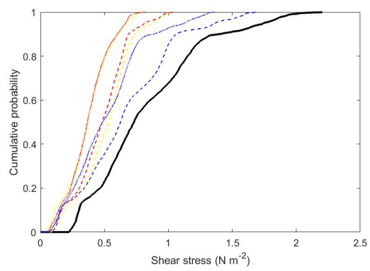


(d) CF of depth

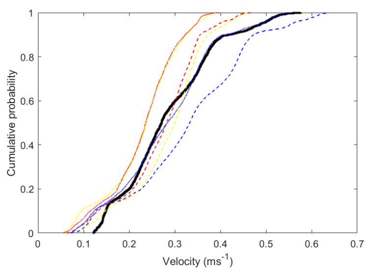
Figure C-4: Effect on hydraulic parameters due to the minimum usage of KWG at 75% market penetration rate for the pipe network of 160mm diameter and slope of 1:250



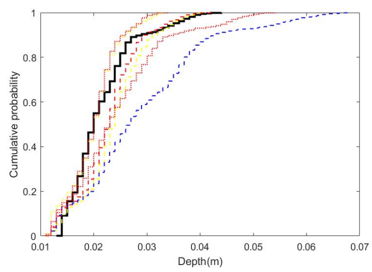
(a) Flowrate



(b) CF of shear stress

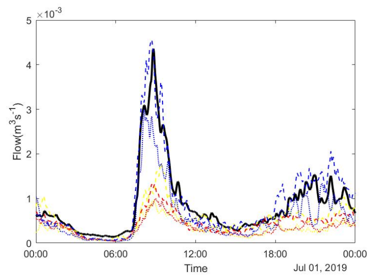


(c) CF of velocity

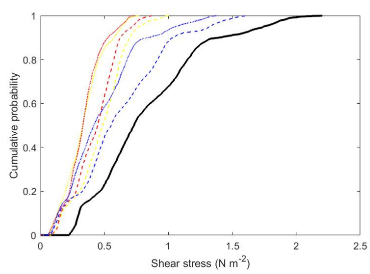


(d) CF of depth

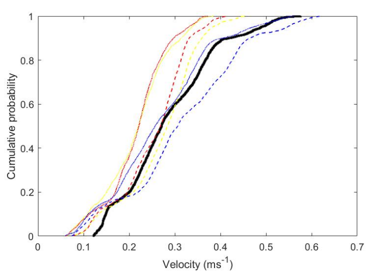
Figure C-5: Effect on hydraulic parameters due to the maximum usage of KWG at 50% market penetration rate for the pipe network of 160mm diameter and slope of 1:250



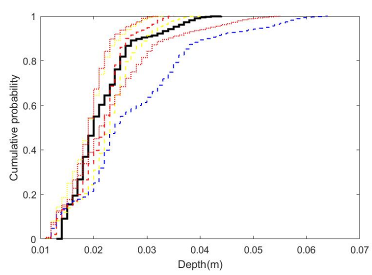
(a) Flowrate



(b) CF of shear stress

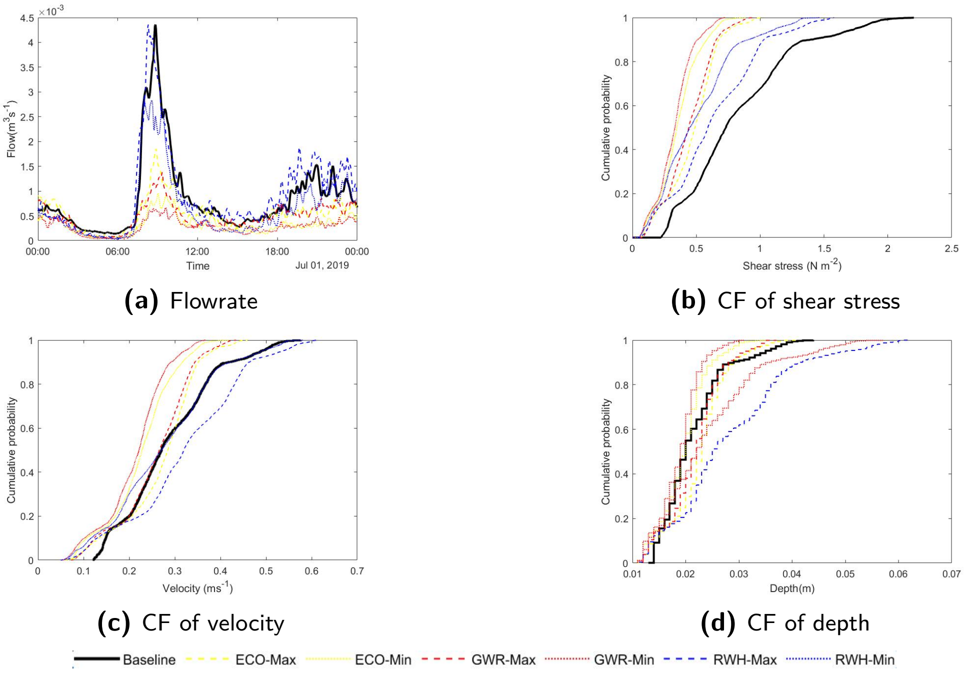


(c) CF of velocity



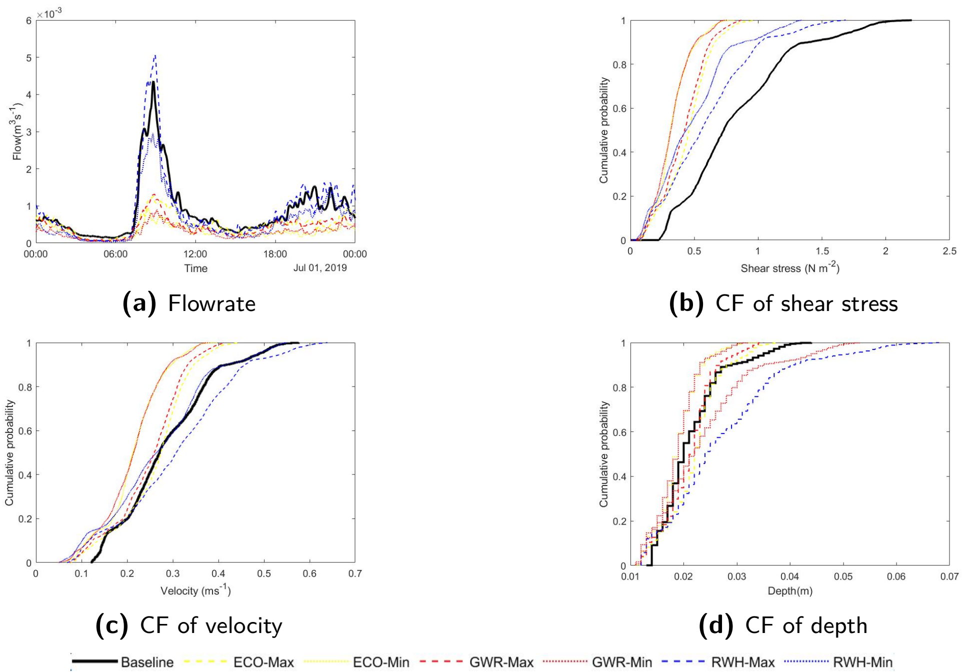
(d) CF of depth

Figure C-6: Effect on hydraulic parameters due to the minimum usage of KWG at 50% market penetration rate for the pipe network of 160mm diameter and slope of 1:250



(a) Flowrate **(b)** CF of shear stress **(c)** CF of velocity **(d)** CF of depth

Figure C-7: Effect on hydraulic parameters due to the maximum usage of KWG at 25% market penetration rate for the pipe network of 160mm diameter and slope of 1:250



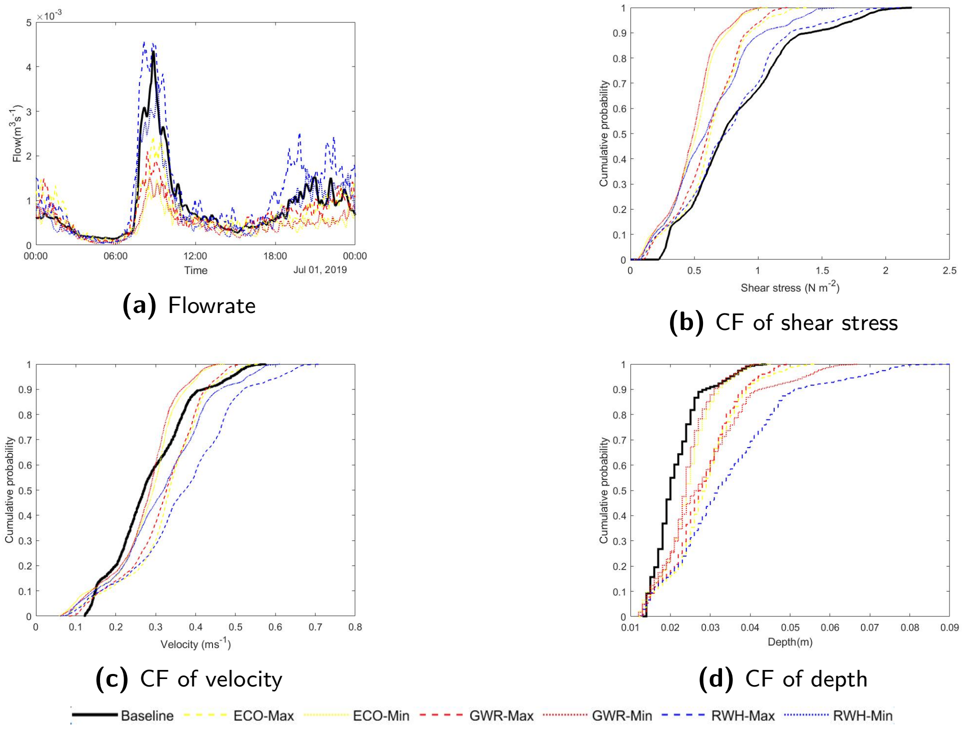
(a) Flowrate **(b)** CF of shear stress **(c)** CF of velocity **(d)** CF of depth

Figure C-8: Effect on hydraulic parameters due to the minimum usage of KWG at 25% market penetration rate for the pipe network of 160mm diameter and slope of 1:250

Appendix D

Appendix-4

D-1 New sewer design: 110mm diameter and 1:250 slope



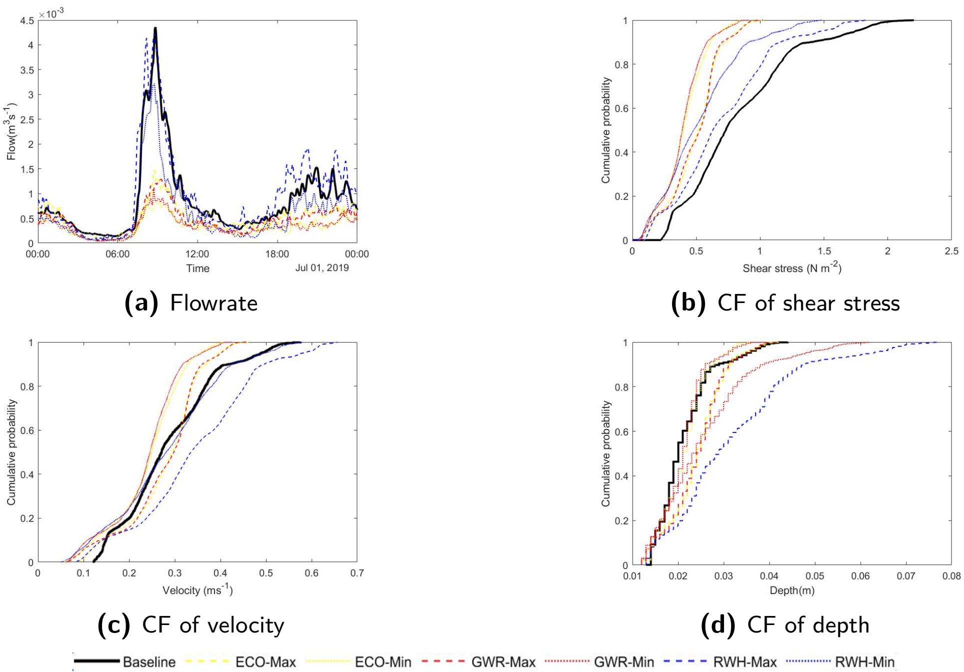
(a) Flowrate

(b) CF of shear stress

(c) CF of velocity

(d) CF of depth

Figure D-1: Effect on hydraulic parameters due to the maximum usage of KWG at 100% market penetration rate for the pipe network of 110mm diameter and slope of 1:250



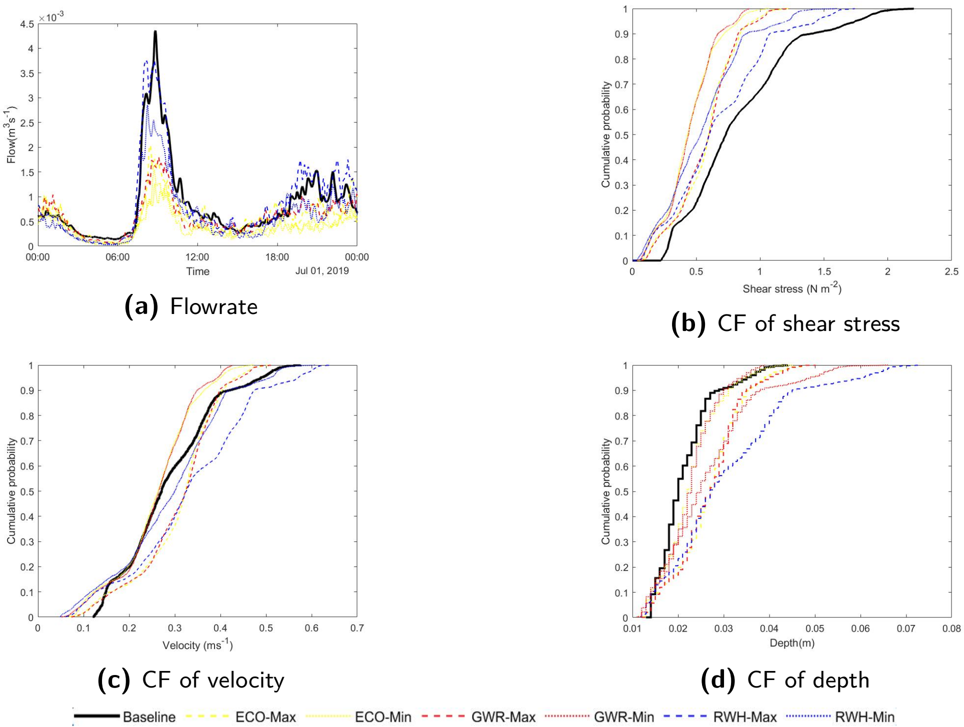
(a) Flowrate

(b) CF of shear stress

(c) CF of velocity

(d) CF of depth

Figure D-2: Effect on hydraulic parameters due to the minimum usage of KWG at 100% market penetration rate for the pipe network of 110mm diameter and slope of 1:250



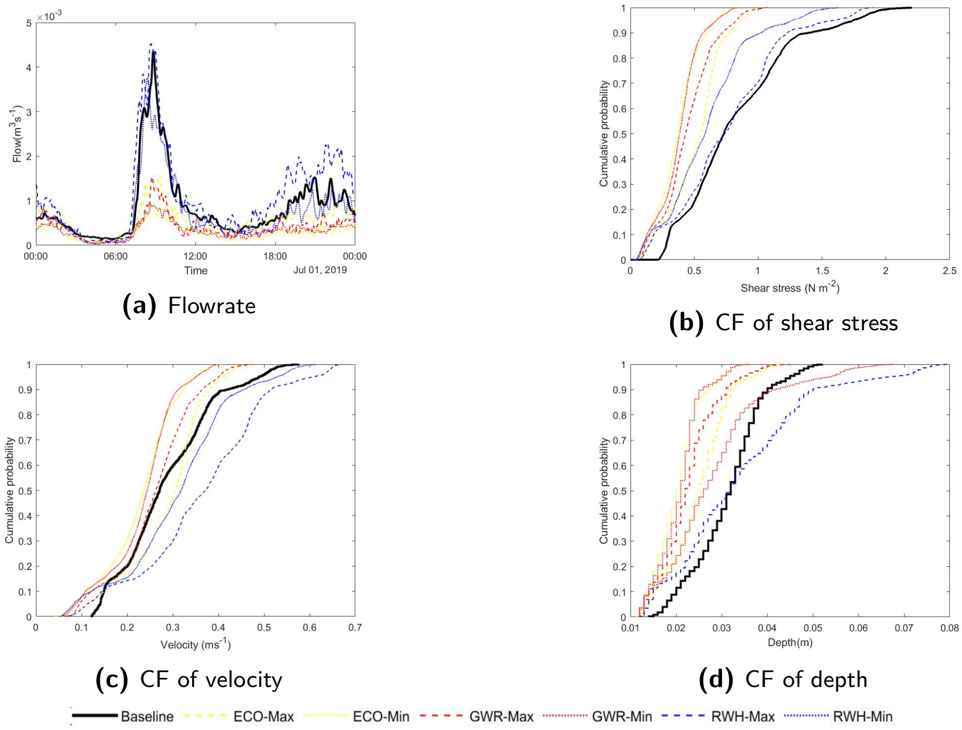
(a) Flowrate

(b) CF of shear stress

(c) CF of velocity

(d) CF of depth

Figure D-3: Effect on hydraulic parameters due to the maximum usage of KWG at 75% market penetration rate for the pipe network of 110mm diameter and slope of 1:250



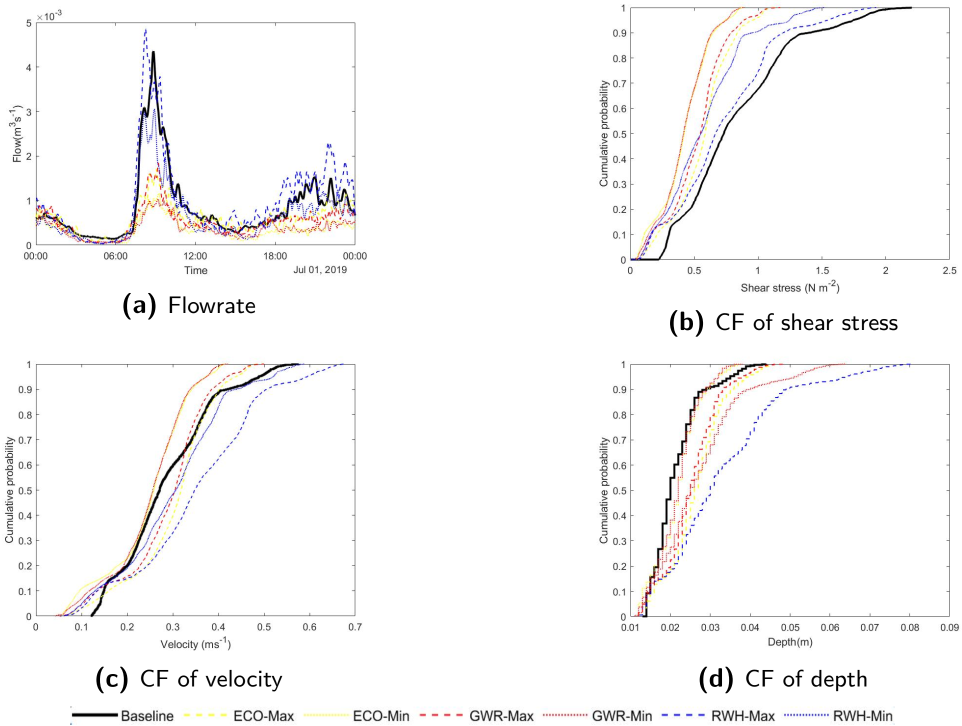
(a) Flowrate

(b) CF of shear stress

(c) CF of velocity

(d) CF of depth

Figure D-4: Effect on hydraulic parameters due to the minimum usage of KWG at 75% market penetration rate for the pipe network of 110mm diameter and slope of 1:250



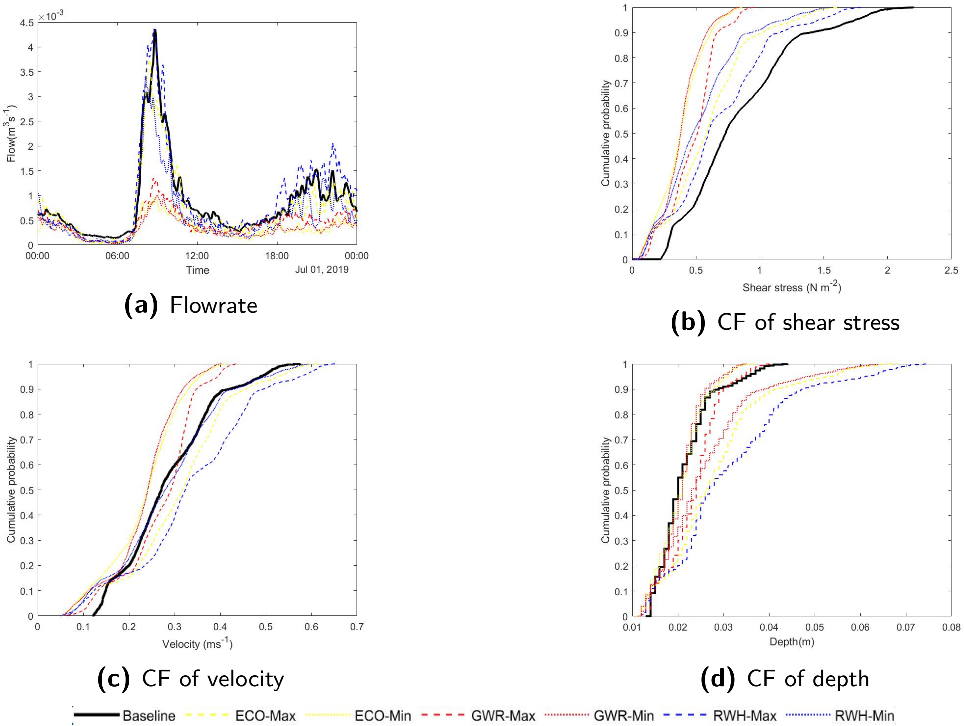
(a) Flowrate

(b) CF of shear stress

(c) CF of velocity

(d) CF of depth

Figure D-5: Effect on hydraulic parameters due to the maximum usage of KWG at 50% market penetration rate for the pipe network of 110mm diameter and slope of 1:250



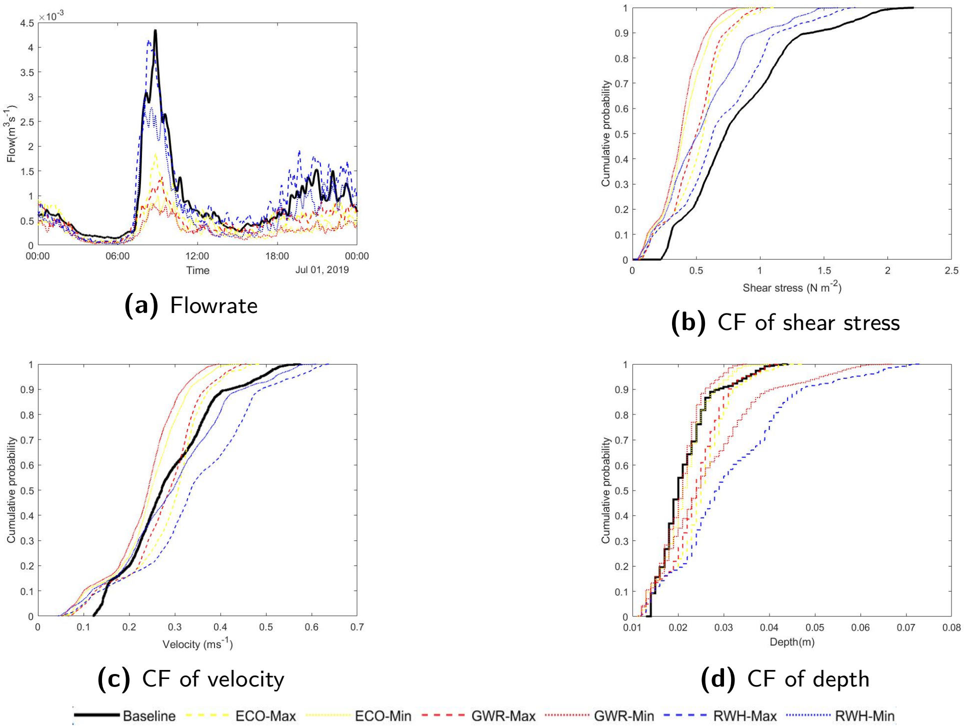
(a) Flowrate

(b) CF of shear stress

(c) CF of velocity

(d) CF of depth

Figure D-6: Effect on hydraulic parameters due to the minimum usage of KWG at 50% market penetration rate for the pipe network of 110mm diameter and slope of 1:250



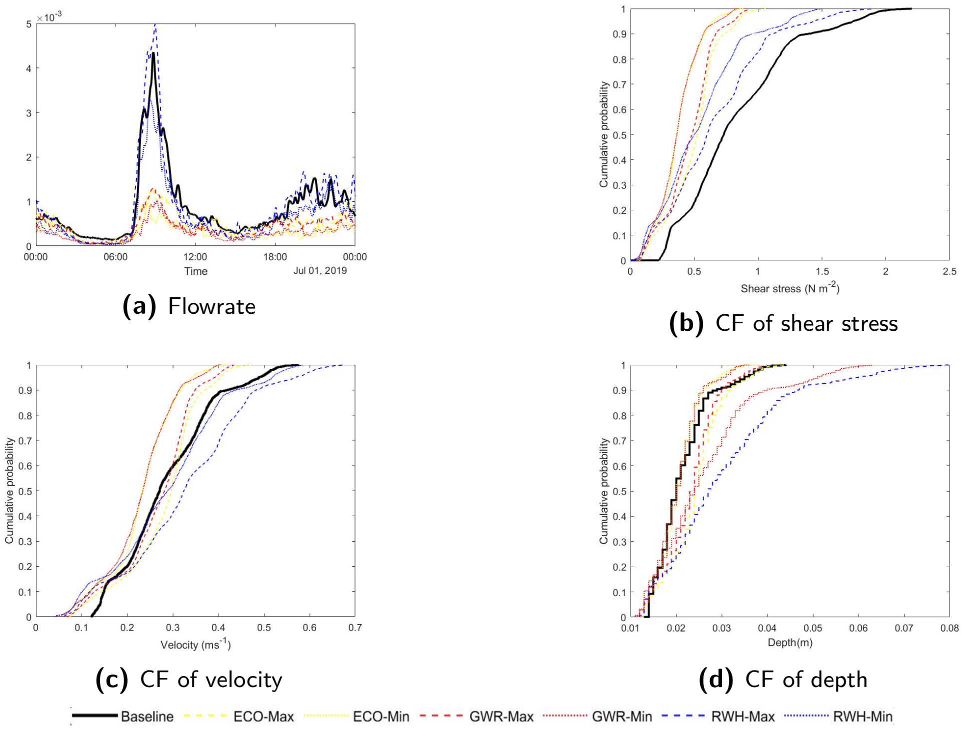
(a) Flowrate

(b) CF of shear stress

(c) CF of velocity

(d) CF of depth

Figure D-7: Effect on hydraulic parameters due to the maximum usage of KWG at 25% market penetration rate for the pipe network of 110mm diameter and slope of 1:250



(a) Flowrate

(b) CF of shear stress

(c) CF of velocity

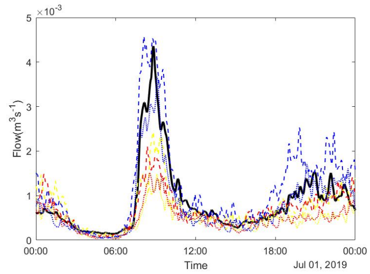
(d) CF of depth

Figure D-8: Effect on hydraulic parameters due to the minimum usage of KWG at 25% market penetration rate for the pipe network of 110mm diameter and slope of 1:250

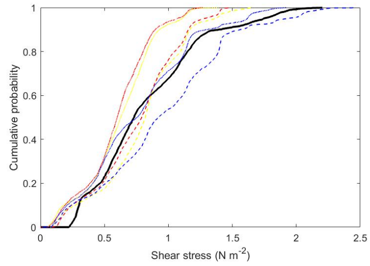
Appendix E

Appendix-5

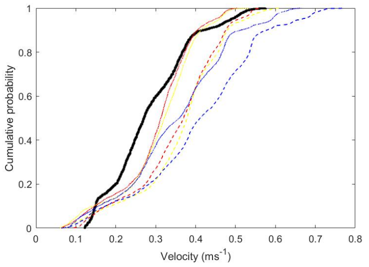
E-1 New sewer design: 110mm diameter and 1:160 slope



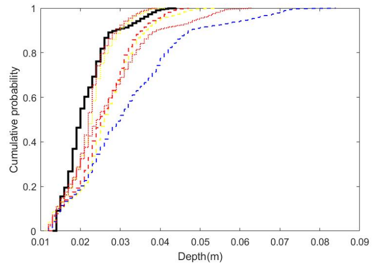
(a) Flowrate



(b) CF of shear stress

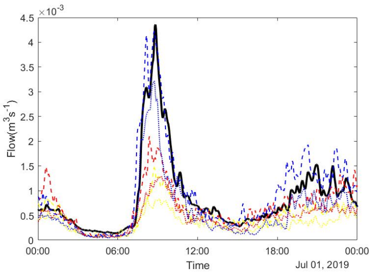


(c) CF of velocity

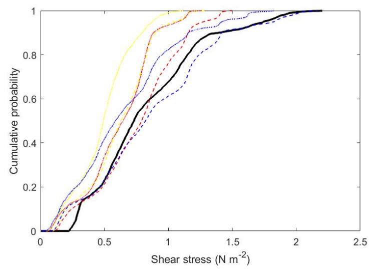


(d) CF of depth

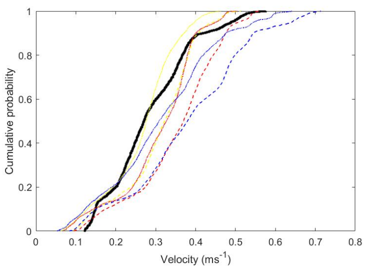
Figure E-1: Effect on hydraulic parameters due to the maximum usage of KWG at 100% market penetration rate for the pipe network of 110mm diameter and slope of 1:160



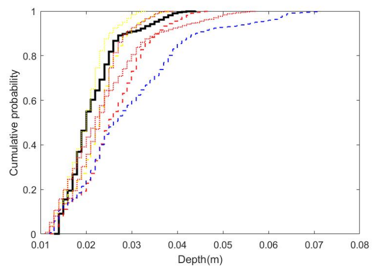
(a) Flowrate



(b) CF of shear stress

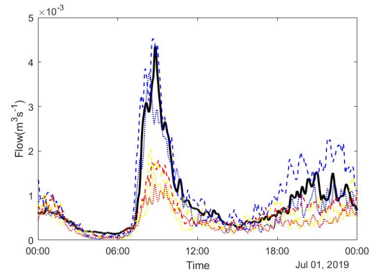


(c) CF of velocity

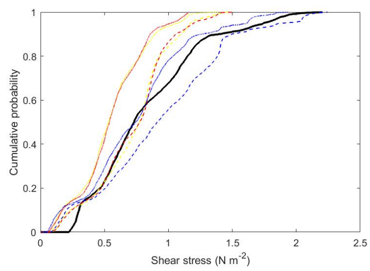


(d) CF of depth

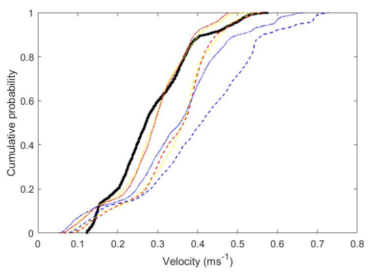
Figure E-2: Effect on hydraulic parameters due to the minimum usage of KWG at 100% market penetration rate for the pipe network of 110mm diameter and slope of 1:160



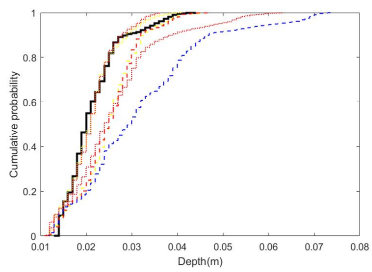
(a) Flowrate



(b) CF of shear stress

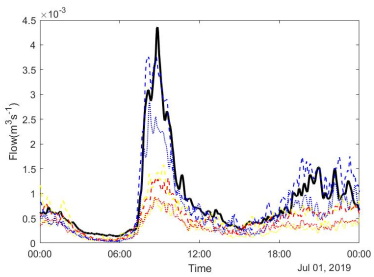


(c) CF of velocity

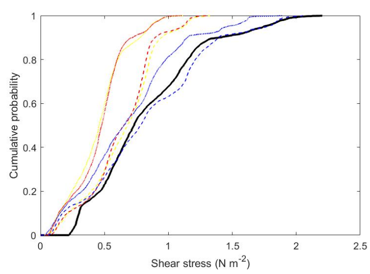


(d) CF of depth

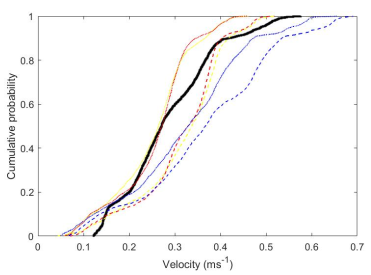
Figure E-3: Effect on hydraulic parameters due to the maximum usage of KWG at 75% market penetration rate for the pipe network of 110mm diameter and slope of 1:160



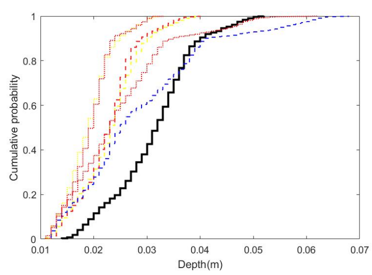
(a) Flowrate



(b) CF of shear stress

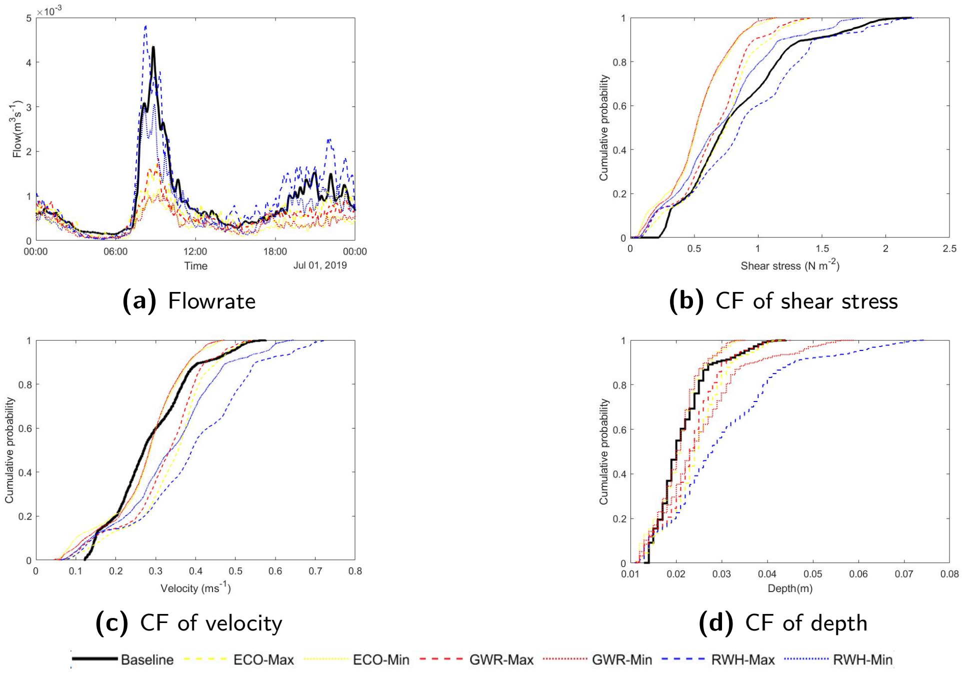


(c) CF of velocity



(d) CF of depth

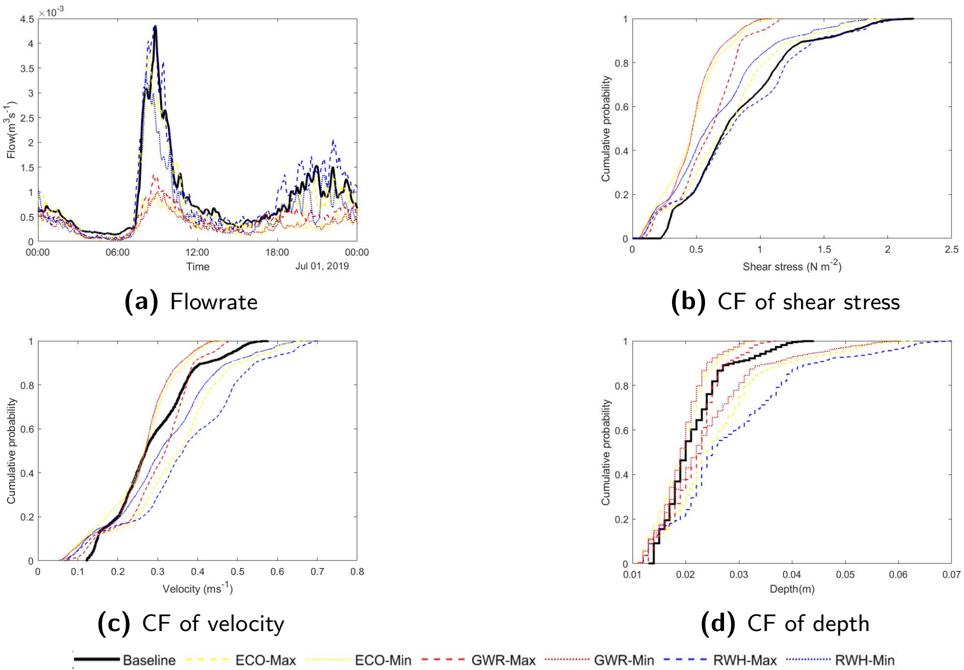
Figure E-4: Effect on hydraulic parameters due to the minimum usage of KWG at 75% market penetration rate for the pipe network of 110mm diameter and slope of 1:160



(a) Flowrate **(b)** CF of shear stress

(c) CF of velocity **(d)** CF of depth

Figure E-5: Effect on hydraulic parameters due to the maximum usage of KWG at 50% market penetration rate for the pipe network of 110mm diameter and slope of 1:160



(a) Flowrate **(b)** CF of shear stress

(c) CF of velocity **(d)** CF of depth

Figure E-6: Effect on hydraulic parameters due to the minimum usage of KWG at 50% market penetration rate for the pipe network of 110mm diameter and slope of 1:160

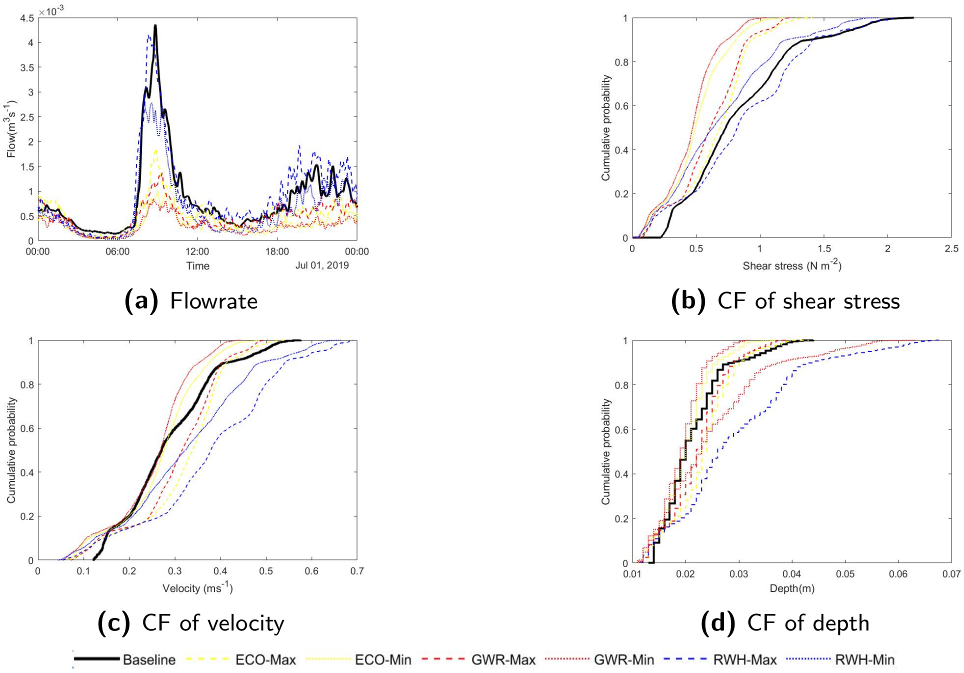


Figure E-7: Effect on hydraulic parameters due to the maximum usage of KWG at 25% market penetration rate for the pipe network of 110mm diameter and slope of 1:160

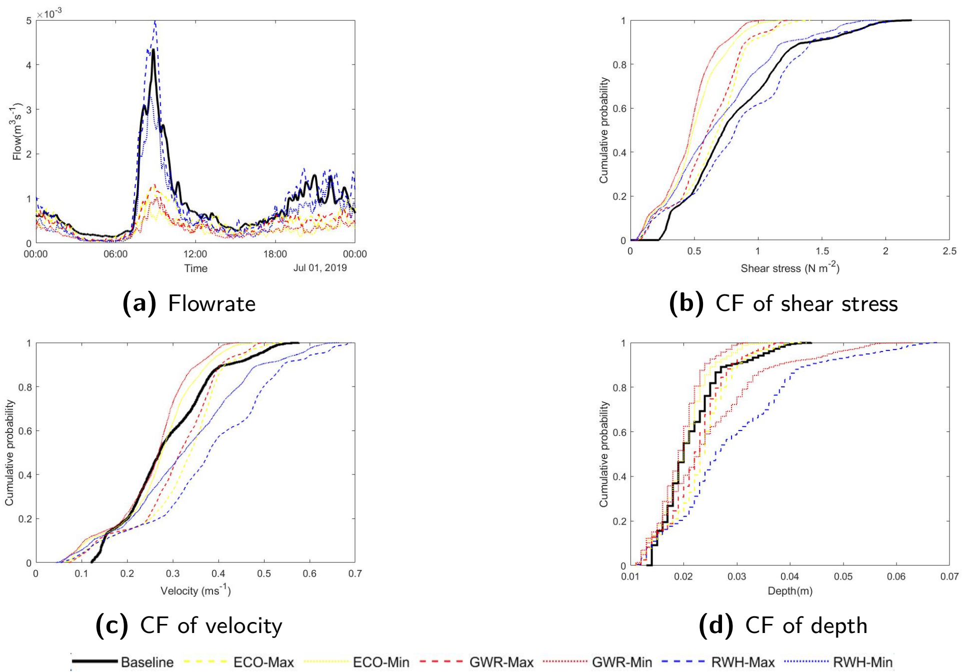


Figure E-8: Effect on hydraulic parameters due to the minimum usage of KWG at 25% market penetration rate for the pipe network of 110mm diameter and slope of 1:160

Glossary

List of Acronyms

GW	Greywater
GWR	Greywater Reuse
RWH	Rainwater Harvesting
KWG	Kitchen Waste Grinder
MS	European Member States
COD	Chemical Oxygen Demand
BOD	Biochemical Oxygen Demand
TKN	Total Kjeldahl Nitrogen
TPH	Total Phosphorous
TSS	Total Suspended Solids
RSS	Residual Suspended Solids
WC	water closet