GIMA Geographical Information Management and Applications

Modelling Wastewater Quantity and Quality in Mexico

-- using an agent-based model

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ABSTRACT

Wastewater is a key element in regional and global water circles, and the discharge of a large quantity of untreated wastewater is posing serious threats to the environment and public health in Mexico. To have a thorough understanding of the mechanism of how wastewater is produced and flows in the city is a crucial step to address the problem. The thesis built a network-based ABM (agent-based model) to simulate the wastewater-related socio-ecological system, taking Huehuetla, Mexico as the study area. It aims to represent the change of wastewater quantity and quality over time and space that is caused by human behaviour, at the hourly temporal resolution.

For this purpose, how local people decide on their activities and how they interact with each other and with the environment are modelled. People's activities defined here refer to the human water-use practices that could generate wastewater, including individual water-use activities (i.e., the use of bath, wash basin, toilet, and shower) and collectives' behaviour (i.e., the use of kitchen sink and washing machine, industrial processes, and socio-economic activities). The exact activity adopted by an individual at a certain tick is determined by its own decision-making rule that considers personal characteristics (i.e., age, educational age, water-saving consciousness, and employment status) and exogenous factors, such as weather (i.e., temperature and precipitation) and intervention actions taken by the government (i.e., organise a water-saving campaign). Weather has a direct impact on individual decision-making rules, while the water-saving campaign comes into play by raising individual water-saving awareness that is also influenced by others via the social network. On the other hand, wastewater quality is calculated based on the quantity and concentrations of TSS, BOD5, and COD in wastewater from various sources. Meanwhile, wastewater flow along the sewerage network in the city towards the wastewater treatment plant is simulated mathematically.

The thesis provides an overall picture of the current situation of wastewater production in the study area by plotting the time series of wastewater inflow and quality to the treatment plant, and analyses the main source of wastewater pollutants – industrial processes, and peak hours of household wastewater production – hours near waking-up time and bedtime. Besides, it also shows the role the government plays in controlling wastewater quantity and quality to improve the current wastewater situation. Scenario experiments are conducted in the study area to test the optimal place and timing of a water-saving campaign, with the conclusion being that the campaign held at school in March can lead to the maximum effect on reducing household wastewater production.

Keywords: agent-based modelling (ABM), network-based ABM, wastewater quantity and quality, human water-use activities, wastewater in Mexico

Contents

1 INTRODUCTION

1.1 PROBLEM STATEMENT

Wastewater is a key element in the local and global water circle, but the discharge of a large quantity of untreated wastewater is posing serious threats to the environment and public health in Mexico. For a better management of wastewater, many wastewater generation models were proposed based on data-driven or mathematical models, but they cannot explain the hidden causes behind wastewater generation. Agent-based modelling is a powerful tool to simulate human-environment interactions in real life and to analyse the anthropologic impetus behind such phenomena.

1.1.1 WASTEWATER

Wastewater (also waste water, as shown in Figure 1.1) does not have a single pinpoint definition, but it is widely accepted that wastewater refers to the contaminated water caused by human activities (“wastewater”, 2020). It includes the used water from humans’ domestic, commercial, agricultural, and industrial activities, as well as the storm runoff, which washes off the roads and rooftops (Tuser, 2020). In a typical water-using situation, the generated wastewater will be transported to a sanitation system and then be treated there through physical, chemical, and biological processes (as shown in Figure 1.2), followed by being discharged into the environment, e.g., rivers and seas (Von Sperling, 2007).

Figure 1.1: Wastewater (Source: Google images)

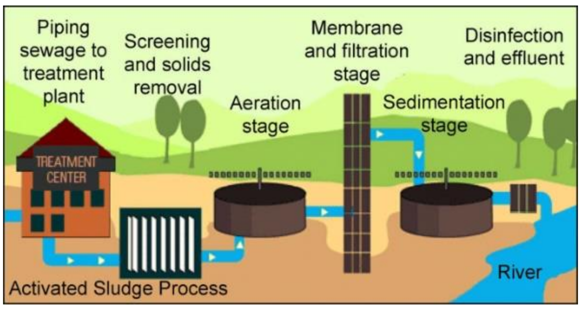


Figure 1.2: Processes in wastewater treatment plant (Source: Baharvand & Daneshvar, 2019)

In arid and semi-arid regions where water demand exceeds water availability, the water scarcity problem has driven wastewater reclamation as an important source of water supply (Voulvoulis, 2018). Even in countries with low water stress, the productive reuse of wastewater is also expanding with the increasing volume of wastewater generated (Qadir et al., 2010). For instance, irrigation with wastewater is adopted worldwide to support agricultural products, covering nearly 10% of the global irrigated land (Jiménez, 2006). In this way, the quality of water that is bounded by humans' daily life largely depends on the generation, treatment, and discharge of wastewater. However, countries at different income levels have different treatment ratios for wastewater (see Figure 1.3): on average, high-income countries have 70% of wastewater treated, upper-middle-income countries 38%, lower-middle-income countries 28%, and low-income countries only 8% (Sato et al., 2013).

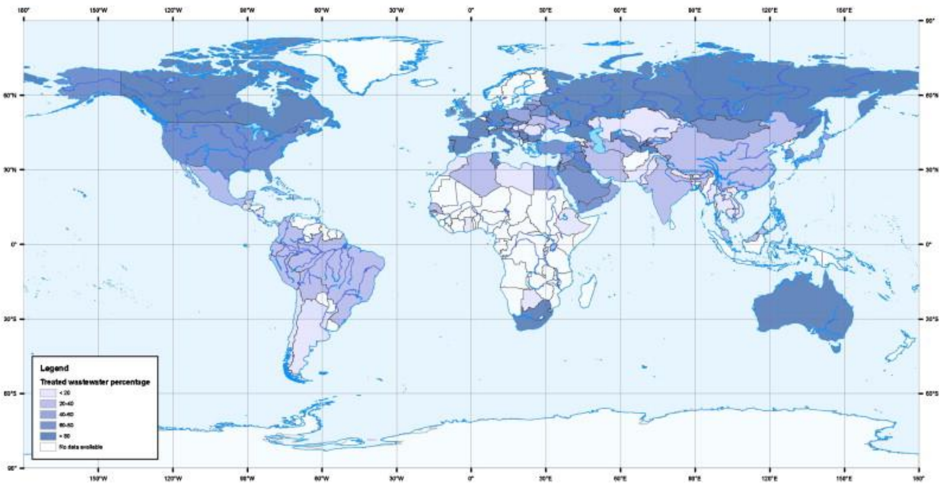


Figure 1.3: Ratio of treated wastewater to total generated wastewater (Source: Sato et al., 2013)

Once untreated and inadequately treated wastewater is discharged into the environment, it will cause severe environmental and health hazards. For one thing, wastewater carries various and abundant organic and inorganic pollutants (Vogelsang et al., 2006; Hajiali &Pirumyan, 2018). The resultant excessive nutrient loading is one sort of representation of microbial pollution, and excessively turbid effluent can disrupt land characteristics in the long run (Naidoo & Olaniran, 2014). For another, wastewater contains a lot of metal icons and chemical matters that are toxic to human health, e.g. aluminium, iron and phosphorus (Saxena et al., 2016; Chowdhary et al., 2018; Wong et al., 2018). Meanwhile, potential pathogenic organisms from different origins, e.g. viruses, bacteria, and parasites, can ferment in and transmit via wastewater (Shuval, 2003; Salgot et al., 2006). About 1.8 million children die from diarrheal each year, a disease mainly caused by bacteria living in brackish rivers and coastal waters (Peter & Umar, 2018).

In addition, wastewater plays a vital role in the regional and global water circle that has a profound impact on climate change. Therefore, wastewater management, as a key step in better water management, is gaining more attention.

1.1.2 WASTEWATER GENERATION FORECASTING MODELS

For better wastewater management, short-term forecasting of wastewater production is a field of much interest. It is also beneficial for the optimisation of the treatment process (El-Din & Smith, 2002). Thus, there are many methods developed for such purposes, such as time series triangle function method, artificial neural network method, grey system theories method and wavelet analytical method (Liu & Zhang, 2002).

Wąsik & Chmielowski (2016) applied seasonally exponential smoothing algorithms to determine the daily change of the sewage inflow into a wastewater treatment plant (WWTP). For the same research objective, El-Din & Smith (2002) developed an artificial neural network (ANN) model, while Boyd et al. (2019) provided an autoregressive integrated moving average method for separate municipal and rural WWTPs. To deal with the uncertainty problem, Jiang & Liu (2016) explored the periodic fluctuation of wastewater production in megacities by a probability model–driven statistical learning approach which integrated a wavelet denoising model, a Gaussian mixture model and a hidden Markov model.

An increasing number of forecasting models for wastewater generation were built, and all have their own strengths either in model establishing, predicting accuracy, speed, or applicability (Li et al., 2019; Man et al., 2019). However, these equation-based mathematical models focus only on algorithms to implement the behaviour within the model, rather than evaluating sets of system variables (Parunak et al., 1998). That is to say, they are all computational models and do not form a deep understanding of the underlying causes of wastewater generation. Nevertheless, these hidden influential factors, e.g., the subjective preference of people for certain water use activities and the impact of water-saving strategies, are vital in quantifying and explaining uncertainties in wastewater generation process. Moreover, figuring out these causes and their mechanisms for producing wastewater can help the government make proper management policies.

1.1.3 AGENT-BASED MODELLING

Agent-based modelling (ABM) is a typical bottom-up method that simulates dynamic processes in terms of agents and their interactions (Macal & North, 2014). An agent is defined as an autonomous computerised individual or object with attributes and behaviour, projecting the characteristics of an individual, group, or even non-living entity in real life (Wilensky & Rand, 2015). Agents, including their states and decision-making rules, are usually constructed based on actual experiences, so the modelling process is much closer to our natural thinking process. Besides, the heterogeneity in individuals in terms of behavioural rules, the stochasticity in a phenomenon can be easily represented and tackled in an agent-based model (Helbing, 2012).

Due to its powerful capability in simulating the reality, ABM has been promiscuously employed in many fields in recent decades (Heckbert et al, 2010; An, 2012). With no doubt, it is also common in studies of water use, water demand and water management. Some researchers focused on behavioural patterns of water users (Athanasiadis & Mitkas, 2005; Chu et al., 2009; Linkola et al., 2013), while others engaged in the interactions among different agents, e.g. households, the government and water utility managers (Yuan et al., 2014; Koutiva & Makropoulos 2016; Ali et al., 2017; Darbandsari et al., 2017). Some built single agent-based models (Chu et al., 2009; Linkola et al., 2013; Ali et al., 2017), whereas others hybridised agent-based models with other econometric models (Athanasiadis et al., 2005; Koutiva & Makropoulos 2016) or dynamic social models (Galán et al., 2009).

Compared to other approaches, ABM offers many advantages in studying the mutual interaction between autonomous agents and the behaviour of water users (Rixon et al., 2007): 1) it provides a more natural description of the socio-ecological system; 2) it can better deal with the heterogeneity in a population of agents; 3) it can express the spatial variability in a more explicit way; 4) it can capture emergent global changes caused by local interactions (Cominola et al., 2015).

Nevertheless, there are few studies that applied ABM in wastewater. Even though the human behaviour regarding wastewater generation is closely linked to those of water use, some of these water use activities do not produce wastewater, e.g., gardening and evaporation. Moreover, research in water use only focuses on the quantity and not on the quality which is an important element in wastewater modelling. Thus, according to precursors' research experience in applying ABM to water use field, it should be promising to conduct an independent research on wastewater with ABM.

1.1.4 STATUS-QUO IN MEXICO

The thesis will take Huehuetla, a typical Mexican city, as the study area. Mexico, a developing country with 1,964,375 km2 territory and around 128 million inhabitants, ranks the 93rd place out of 200 countries worldwide in terms of per capita renewable water (Conagua-Semarnat, 2017). With the rapid growth of population and economy, the state of water resources is deteriorating, whereby the local government considers the lack of clean water as one of their national security issues (American CIA, 2020).

Mexico is now facing a serious water crisis: 1) severe water scarcity: 8 out of 13 hydrological-administrative regions are always experiencing high or very high water stress (Conagua-Semarnat, 2008; Conagua-Semarnat, 2010; Conagua-Semarnat, 2016); 2) Heavy contamination (Godinez Madrigal et al., 2018). Almost 20% of aquifers and over 30% of surface water were in a high level of contamination in 2017 (Conagua-Semarnat, 2017); 3) high vulnerability to stochastic meteorological events (Conagua-Semarnat, 2018).

The reasons for these phenomena are basically: 1) inadequate wastewater treatment: a large quantity of wastewater (about 62% of industrial and 42% of municipal wastewater) was discharged without treatment (Conagua-Semarnat, 2018); 2) insufficient sanitation measures: 8.6% of people were still not covered by the national sanitation network in 2017 (3.4% in urban areas and 25.8% in rural areas) (Conagua-Semarnat, 2018). Consequently, most Mexican rivers are polluted, and the quality of drinking water cannot be guaranteed, which is likely to bring about widespread public health problems (Godinez Madrigal et al., 2018).

The Mexico government has carried out a water reform aiming at nationwide water supply and sanitation (Grafton et al., 2019), but it did not lead to satisfying outcomes (Smith, 2017). That is partly because the considerations in water management and governance were not sufficient. In fact, to improve the current status of water resources, it is far from enough to merely construct water infrastructures nationwide. It is also necessary to figure out the rationale behind water use behaviour and the mechanism of wastewater generation. Only by finding out the underlying causes, can the government and related sectors make proper policies or take effective measures to improve the current condition and to ensure a sustainable water supply.

1.2 OUTLINE OF THE THESIS

1.2.1 RESEARCH OBJECTIVE

The research aims to develop a generic agent-based model, simulating the dynamic change of wastewater quantity and quality (WWQQ) over space and time at the city level. To figure out the mechanism of wastewater generation, the relationship between wastewater production and human behaviour as well as the factors affecting human's decision-making process, e.g., weather condition and individual consciousness, will be explored. For another, wastewater quality will be evaluated by the contents of certain indicators, i.e., total suspended solids (TSS), five-day biological oxygen demand (BOD5), and chemical oxygen demand (COD). Moreover, the model will be calibrated and validated by results of previous research, and scenario experiments will be carried out to test the effect of government strategies, so that a few suggestions are put forward.

1.2.2 RESEARCH QUESTIONS

Therefore, the core question of the thesis is set as:

> *How can the quality and quantity of wastewater in the urban system of Huehuetla be simulated to gain a better understanding of wastewater fluctuations at the treatment plant?*

To make the core question more concrete, several specific sub-questions are put forward:

1. How can we model wastewater generation and flow in the catchment?

- Which basic elements are included, and how do they interact with each other and the environment? (in terms of the wastewater quantity)
- How to model movements of agents and collectives' behaviour?
- How can the wastewater quality be assessed?
- How to model the flow of wastewater in pipelines?

2. How can we validate the model?

- In terms of wastewater quantity
- In terms of wastewater quality

3. How can this model be used to design different government strategies for controlling the quantity and quality of wastewater?

- Should a campaign be launched via blocks or schools?
- When is the best timing (month) for a campaign?

1.2.3 RESEARCH APPROACHES

For research question 1, an agent-based model will be framed. Individuals in real life are simulated by agents in modelling. They are assigned with attributes, such as age, educational age and water-saving consciousness, and water-use behaviour at home that are divided into practices of using the bathtub, the toilet, the washbasin, and the shower. Different groups of individuals can make up disparate collectives via their movements during the day. Each collective has its own behaviour of wastewater generation. Wastewater quality is calculated based on the generic wastewater quality of different provenances whose data are got by consulting the literature, and the in-situ wastewater production at the provenance in the study area. The flow of wastewater in pipelines is assumed to be like the movement of solid particles inside the pipe.

Regarding research question 2, the lack of monitoring data makes it impossible to validate the model with empirical data, thus the validation process can only be carried out by comparing the model results with results of previous research. The items in comparison are all at the aggregate level, including the daily wastewater production per capita, the proportions of the wastewater from different sources accounting for the total amount, as well as the time series of hourly production in a day, etc.

With regard to research question 3, the government can help to control the wastewater production and quality by making diversified strategies, but the only type of strategy in consideration in the thesis is organising a water-saving campaign. A campaign plays a role in boosting individual water-saving consciousness, thereby reducing the total wastewater production. The effects of a campaign held in different locations and timing are experimented based on the validated model, so that to figure out the optimal place and month to organise the campaign.

1.2.4 STRUCTURE OF THE THESIS

The rest of this thesis is structured as follows: Chapter 2 – literature review, reviews previous literature relevant to all facets of research questions; Chapter 3 – methodology, shows in detail how the agent-based model is conceptually built step-by-step. Chapter 4 – implementation and calibration, includes the parameterisation of the study area and validation of the model, as well as the robustness analysis and sensitivity analysis. Chapter 5 – results and analysis, analyses the model results and conducts experiments for different strategies. Chapter 6 – conclusions and discussions, responds research questions and discusses limitations in the model design as well as puts forward recommendations for future development.

2 LITERATURE REVIEW

There is little research on human behaviour that produces wastewater, but numerous research on humans' water-use behaviour has been carried out in the past decades. The thesis learns from the strengths of predecessors and accommodates the analysis methods in applications of water use to the field of wastewater generation.

2.1 ABM FOR HOUSEHOLD WATER-USE ACTIVITIES

It is widely acknowledged that agent-based modelling (ABM) is a powerful tool to disaggregate a complex system into simple components with special state variables and behaviour to simulate their decision-making processes and their interactions with other entities in the system (Crooks & Heppenstall, 2012). In systems regarding water use, ABM has been already a dominant and verified approach to explore the mechanism of human behaviour. This research involved all aspects of human behaviour and water use: the temporal scale, influential factors, individual decision-making mechanism and quantification methods.

2.1.1 LONG-TERM VS. SHORT-TERM

As the first element in consideration in water use systems, the temporal scale lays the foundation for the research scope. It is represented by the time step that the research adopts. There are several types of temporal scales in research, from long term to short term: yearly, quarterly, monthly, daily, and hourly. Different scales apply to different research objectives.

Research at yearly time step mainly aimed at exploring the dynamic change of patterns of human water-use behaviour over a long temporal horizon, and the driving forces of this change, e.g., the economic growth, the new-generation/upgraded technology in the market and water policies. For instance, Chu et al. (2009) developed a RWUM model to reveal the change of residential water-use behavioural patterns in Beijing at a yearly step from the year 1985 to 2030. The research noticed an obvious shift of the dominant water end-use from faucet and clothes washing to bathing and toilet flushing over the past decades, and the main cause was the replacement of less-efficient water devices with high-efficiency, which resulted from a high yearly market penetration rate of advanced devices with stricter standards and the promotion of water reuse policies set by the government. A similar research was conducted by Darbandsari et al. (2017) who built a UHBM model to simulate the yearly water consumption of residential water users in Tran, Iran.

The quarterly time step is often used in studies of exploring the regularities of human water-demand or water-use behaviour considering the influence from socioeconomic or sometimes geographic aspects at a medium temporal scale, e.g., urban dynamics. For instance, Galán et al. (2009) simulated the individual evolution of water consumption and computed the aggregated family water demands within a ten-year timeframe, with each time step representing 3 months. Instead of the water pricing, it considered the evolution of public awareness about water, the migratory movement of families and the adoption of an innovation within a dwelling, all of which could considerably change the individual water-use behaviour and their water consumption within three months.

Research based on monthly time step usually targeted at evaluating or predicting the effects of various actions taken by the government on reducing the water consumption or water demand, such as a minor change in water price or a water-saving campaign. A monthly time step is quite appropriate for such objectives because these actions come into effect gradually. For instance, Athanasiadis et al. (2005) built a DAWN model to estimate the future water demands of residents at a monthly time step in five different water-pricing scenarios with an implementation of an information and education policy. The research result indicated that implementing an education and information policy of medium scale whose effects are proliferating over time has similar effects as the measure of increasing water price by 5%, and a major conservation policy may yield water savings of over 5% of total demands.

The daily temporal scale was used in relatively micro-level simulations, which basically researched the individual water use behaviour emerged from discrete events such as social interactions. For instance, Rixon et al. (2007) simulated the daily water use of residents under the effects of social networks (including the friend networks on water-saving beliefs and the utility campaigns when water resources reaching critical levels) and tariff structures, which implied that individual water use behaviour was influenced by its water-saving beliefs. The model results demonstrated social networks could bring about a significant reduction in simulated daily water use of residents, under a flexible tariff regime which ensured most people to be affordable to their water bills.

Hourly-time-step simulations focus on the impact of exact human activities on the water use quantity, e.g., cooking and showering. Such research usually considers individuals as agents and their behaviour are the real-world activities people do in their daily lives. For instance, Linkola et al. (2013) simulated the hourly water-use behaviour of people from three different household types: single, retired couple and family with children, and compared the water use quantity at the household level, at the individual level and at the activity level. The hourly activities include clean body, clean clothes, clean dishes, eat/drink and excrete. The research concluded that a working single has the highest per-agent frequency of showering, whereas families with children most use the bathtub and the retired couple scores the highest in the frequency of using the toilet and kitchen.

Back to the thesis, considering that the objective is to research the relationship between human behaviour and wastewater production, the thesis finally adopts the hourly time step and a single simulation runs for one year. Besides, the peak day production is a key parameter for designing future capital infrastructure capacity of bulk wastewater collection systems (Day & Howe, 2003). Moreover, people's behavioural patterns vary remarkably with personal attributes at such a small temporal scale, so the individuals modelled in the thesis are accordingly classified into four types: children/ preschoolers, teenagers (at school), adults, and seniors.

2.1.2 GLOBAL VARIABLES VS. STATE VARIABLES

Corresponding to the variety of temporal scales, the determinants of human water-use behaviour were also diverse in literature. These factors could be classified by their sources: global (climate) variables and (agents') state variables. In some literature, they were also called physical variables and human/social factors respectively (Corbella & i Pujol, 2009). The former had a homogenous impact on all individual agents, usually including rainfall and temperature, while the latter exerted a heterogeneous impact on agents per se, including individual age, education level, and household size.

After looking into numerous literature, one finding is that many influential factors have been experimented, covering all aspects of water-use behaviour and water consumption. An overview of some important literature and their explored factors is shown in Table 2.1. The most frequent factors are listed in order by their frequency: *household income level > household device ownership > water price = rainfall/precipitation > device efficiency > household size > individual water-conservation consciousness = temperature = campaigns > having a garden? = vacancy rate = social network influence > individual age > individual education level*. All factors make a difference in quantifying individual water use practices, and more water consumption is more likely to occur in families of higher income or having a garden.

One thing worth noting here is the impact of individual water-saving awareness on the reduction in water consumption. The value-attitude-behaviour chain (Homer and Kahle, 1988) suggested that the rise in environmental awareness does not certainly result in a reduction in water use that is still under the influence of other variables, and can lead to only a high possibility of doing so. That is to say, positive intentions to reduce water use do not correspond to actual reductions. However, Domene & Saurí (2006) found that households with a higher score on the index measuring water-conservation habits reduced their water use between 4.3 and 4.6 litre/person/day, and Pinto et al. (2011) corroborated a negative relationship between environmental awareness and wasteful habits. The higher the environmental awareness, the fewer the wasteful habits and the more the water-use reduction. Meanwhile, the positive influence of education on water-saving behaviour was confirmed by Gilg & Barr (2006). Such behaviour, including turning off the shower when soaping up and only using washing machines with a full load, is impacted by household socio-economic characteristics, such as education and opinions about the environment and resource protection (Millock & Nauges, 2010).

Table 2.1: Influential factors in water use

	government measures					technology			individual								household			dwelling							interaction		climate			
	water price	policy	campaigns	metering	billing frequency	device ownership	efficiency	life-span	age	gender	employment	education	nationality	stubbornness	water-saving awareness	tech preference	size	income	having children?	value	size	having garden?	having swimming pool?	use type/vacancy	build year	No. bedrooms	social network	neighboring dissonance	temperature	rainfall	seasonality	water stress
Agthe & Billings, 2002	√					√														√			√	√	√	√						
Ali et al., 2017						√	√										√				√	√			√					√		
Arbués et al., 2003	√				√												√	√	√			√		√		√			√	√		
Athanasiadis et al., 2005	√		√											√	√			√	√			√					√		√	√		
Beal & Stewart, 2014						√																							√	√	√	
Castonguay et al., 2018	√					√									√	√														√		√
Chu et al., 2009	√	√	√			√	√	√										√														
Darbandsari et al., 2017	√		√															√									√		√	√		
Day & Howe, 2003						√	√		√													√										
Galán et al., 2009												√	√			√	√	√		√		√		√	√		√	√				
Koutiva & Makropoulos, 2016	√		√			√			√			√		√	√			√						√			√			√		
Kowalski & Marshallsay, 2005																	√	√						√							√	
Linkola et al., 2013			√	√					√		√				√				√													
Makki et al., 2015						√	√		√	√		√					√	√														
Manouseli et al., 2017		√				√	√										√	√			√								√	√		
Manouseli et al., 2018			√	√		√	√		√					√	√		√										√		√	√		√
Mieno & Braden, 2011	√																√	√						√					√	√	√	
Rixon et al., 2007	√					√	√								√			√			√	√		√								√
Saurií, 2003	√		√				√											√														
Stewart et al., 2009						√	√		√	√	√	√					√	√									√					
Syme et al., 2004															√			√			√	√	√									
Yuan et al., 2014	√		√									√			√			√									√		√	√		

Due to the close relationship between water use and wastewater generation, all these influential factors mentioned above are regarded as the first options of the factors of wastewater generation. However, because of the difference between water consumption and wastewater generation, certain factors are disregarded at the end in modelling. For instance, some water-use activities have no relevance for wastewater generation, e.g., gardening, thus the factor of *having a garden?* is no longer considered. Besides, some factors were resolved in data pre-processing phase, e.g., *vacancy rate*, while some others are excluded because of the lack of data, e.g., *household income level* and *device efficiency*. Finally, the factors selected in the thesis include *household device ownership*, *precipitation*, *household size*, *individual water-saving consciousness*, *temperature*, *water-saving campaigns*, *social network influence*, *individual age*, and *individual education level*. Among all the variables, *individual water-saving consciousness* is given special attention and plays an essential role in modelling.

2.1.3 INTRINSIC MECHANISM VS. EXTRINSIC REGULARITIES

Apart from the variables mentioned above, a dynamic water use system also contains the rules that define how the system develops in time. The most widespread rules can be classified into two categories: intrinsic mechanisms of human decision-making and extrinsic regularities of the dynamic world. The former means the inherent mechanism of agents making decisions, usually for individuals, but also for government sectors and households, whereas the latter reflects the laws of how the external world changes and works, especially the human world.

The decision on water-saving activity is the most common one made by an individual. It is widely considered to be triggered by individual awareness of the environment, also called water-conservation consciousness in some literature. However, this awareness could be the result of the combination of a rise in water price and a campaign about saving water (Linkola et al., 2013), in conjunction with the impact of education (Yuan et al., 2014), or it could also be influenced by the neighbouring attitudes towards water saving (Athanasiadis et al., 2005). Furthermore, the mechanism from developing the awareness to conducting a concrete activity was also considered by Koutiva & Makropoulos (2016). Besides, environmentalist behaviour can also be determined by the same type of behaviour of neighbours straightforwardly without considering the awareness (Edwards et al., 2005).

Other decisions regarding water consumption made by individuals were also modelling in ABMs. For instance, Kandiah et al. (2017) created water user agents and simulated households' decisions on water reuse based on individual adoption or rejection and household attributes, thereby estimating the communitywide acceptance of reclaimed water with consideration of membership in opinion clusters, frequency of discussion, and the structure of social networks. Rasoulkhani et al. (2018) demonstrated that a household's intention to adopt a new water-conservation technology would be affected by a variety of demographic and household characteristics, social network influence, and some external factors, e.g., water price and rebate policy. The location of residence also matters for household water consumption (Galán et al., 2009) and the selection of residence or the decision to migrate to a new place is highly related to household income level and the residence's value and neighbouring dissonance (Benenson et al., 2002).

In addition, extrinsic dynamic regularities also play a role in water consumption at the household level. The most common one is the population dynamics. Ali et al. (2017) stated a typical linear relationship between the water demand and the population growth. Moreover, the regularities in the development and marketisation of new technology that helps to promote water use efficiency was embedded in the ABM of simulating the behaviour of water users (Chu et al., 2009). These dynamics could cause a considerable change in water consumption without influencing human water-use decisions too much.

The timeframe of the model is set to be one year which is enough for population or new technology to change essentially, thus these extrinsic dynamic regularities are excluded from the thesis's research scope. However, the individual water-conservation awareness in the intrinsic decision-making mechanism can change markedly within one year under the influence of governmental policies. This kind of change has an enormous impact on people's water use habits and partly determines their water-use activities, so it plays an important role in water saving and also in wastewater production. That is why this sort of intrinsic mechanism is considered and modelled in the thesis.

2.1.4 DIRECT VS. INDIRECT QUANTIFICATION

There are two ways widely applied to quantify human behaviour in terms of water use: direct and indirect methods. Direct methods aim at establishing mathematical equations between the attributes of individuals or households and the amount of water they used, without considering the exact activities that agents conducted to consume water. For instance, Athanasiadis (Athanasiadis & Mitkas, 2005) estimated the average consumer's water consumption by a hybrid model which introduced social variables into a conventional econometric model.

Indirect methods would usually introduce an intermediate process between attributes of agents and their exact water consumption, simulating the real-life water-use processes. Butler et al. (2018) mentioned that water consumption patterns at the household level depend partially on the type of the water consuming appliances installed in the houses. Memon & Butler (2006) studied the domestic water consumption patterns for single families in the USA and compiled statistics on consumption shares of different water-demanding appliances: washing machine, toilet, shower, bathtub, hand basin, dishwasher, kitchen sink and outside supply (see Figure 2.1). Based on the same classification of domestic appliances that 'use' water, Makropoulos et al. (2008) first proposed the Urban Water Optioneering Tool (UWOT) in which human water-use behaviour within a household block was also classified by these appliances. Later on, the UWOT was further developed by Rozos & Makropoulos (2013). The upgraded UWOT estimated the water consumption based on the use frequencies (per person per day) of these household appliances and their performance parameters. The former information was provided by water users themselves, whereas the latter information was extracted from the technical specifications of these appliances. Until Koutiva & Makropoulos (2016), the UWOT model was integrated with an Urban Water Agent Behaviour model (UWAB) which simulated the mechanism of individual/household attributes changing with time. The integrated model built various time series of use frequencies of domestic appliances for different water user types, and finally worked out the water use quantity at the household level, realising an automatic conversion from individual/household attributes to water consumption.

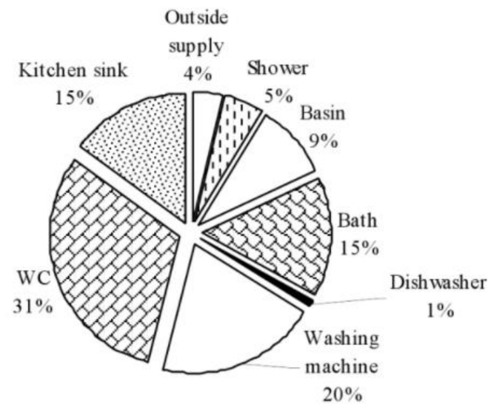


Figure 2.1: Water consumption shares of different micro-components of the household in the industrialised world (Source: Memon & Butler, 2006)

The intuition of simulating the water demands/consumption at the water appliance level in UWOT was then reproduced in an increasing number of simulation models. One of them is the City Water Balance (CWB) model developed by Mackay & Last (2010). It designed a library to which users can add the water using devices in their houses, and the indoor water demand at the residential block level was built based on their selections. Similarly, the WaterMet^2 model developed by Govindarajan (2014) can deal with the urban water systems at four spatial scales. One scale is the indoor scale in which the daily water consumption per capita was split into six types of domestic appliances and fittings. Meanwhile, Linkola et al. (2013) modelled diverse behavioural patterns for individuals with different characteristics, and then connected their hourly activities with their probabilities of using corresponding water-demanding devices, and finally calculated the household water consumption based on the frequencies of using these appliances.

The thesis adopts the indirect way to quantify human behaviour. That is to say, human activities regarding wastewater production are all quantified by the usage of according water-using devices, here are: bathtub, washbasin, toilet, shower, kitchen sink and washing machine. Few local families of the study area installed the dishwasher, so it is excluded from the appliance list. The hourly amount of wastewater produced through a specific device is determined by its use frequency within the hour and its technical parameters, as well as the individual/household attributes or other factors for certain appliances (e.g., kitchen sink and washing machine). Table 2.2 gives the common appliances installed in local families of the study area and their descriptions.

Table 2.2 Installed appliances

Technology	**Comment**
bathtub	Different types of bathtubs. Distinction is mainly based on bathtub holding capacity.
wash basin	Different types of hand basin tabs. Distinction is based on water flow delivery (laminated or aerated flow) and technique diversion to achieve certain water flow.
toilet	Different types of toilet cisterns and toilet technologies. Distinction between different types is mainly based on flushing water consumption.
shower	Different types of shower heads, which can deliver various flow rates. Distinction between different technologies is mainly based on water consumption and user satisfaction.
kitchen sink	Different types of kitchen sink tabs. Distinction is based on water flow delivery (laminated or aerated flow) and technique diversion to achieve certain water flow.
washing machine	A number of washing machines from different manufacturers with diverse specifications.

2.2 EMPIRICAL DATA FOR INDUSTRIAL & SOCIO-ECONOMIC WASTEWATER GENERATION

The research regarding wastewater quality was almost from the aspect of wastewater treatment, rather than modelling their change over space and time. However, most of them provided the actual observed data of wastewater quality of the wastewater from their research area, usually a specific location (e.g., slaughter industry, restaurant, and school). For another, the wastewater generation behaviour of industries and other places involving socio-economic activities not only relate to human behaviour, but also the property of the place itself, e.g., the product type of the industry, the number of customers of the restaurant, and the visiting number of the library. The thesis will take advantage of these research to gain the data of wastewater production per unit product in different places that provide space for industrial or socio-economic activities, and the quality data of wastewater from these places, such as flour industry, bar, hospital, etc.

Table 2.3 Typical wastewater production per unit from different sources

ROOT ITEM	ITEM	SUB ITEM	WASTEWATER PRODUCTION PER UNIT	TYPICAL VALUE	REFERENCE
Family Mill	ice cream	-	0.5 - 2 litre/kg processed milk	1 litre/kg	Nadais et al. 2010; Torres-Sanchez et al., 2014; Kolev Slavov, 2017
	poultry processing	-	3.3 - 6.6 litre/kg bird	4.5 litre/kg	Northcutt & Jones, 2004; Saddoud & Sayadi, 2007; Avula et al., 2009
	cornflour	-	20 - 60 litre/kg flour	40 litre/kg	Movahedyan et al., 2007
	snacks	-	~ 2.5 litre/kg flour	2.5 litre/kg	Jeswani et al., 2015
	coffee	-	8 - 10 litre/kg coffee	9 litre/kg	Cruz-Salomón et al., 2018
	water bottling	-	0.1 - 3.8 litre/kg soft drink	0.8 litre/kg	Pollution Research Group, 2015
	textile	-	~ 120 litre/kg fabric	120 litre/kg	Manenti et al., 2015; Hossain et al., 2018
	leather	-	33 - 45 litre/kg hide	39 litre/kg	Thanikaivelan et al., 2004
	wood	-	~ 1442 litre/m³ wood-based panel	1442 litre/m³	Kloch & Toczyłowska-Mamińska, 2020
	blacksmith	-	~ 25.3 litre/kg steel	25.3 litre/kg	World Steel Association, 2018
	furniture	-	~ 19 litre/kg tile	19 litre/kg	Türkmen et al., 2021
Commercial Place	bakery	-	0.2 - 6 litre/kg bread	3 litre/kg	Chen et al., 2004
	restaurant	full-service	~ 68 litre/seat/day	68 litre/seat/day	Garza, 2006; EPA statistics, 2012(b)
		fast-food	~ 54 litre/seat/day	54 litre/seat/day	Garza, 2006; EPA statistics, 2012(b)
	hotel	-	148 - 287 litre/guest/day	260 litre/guest/day	Smith et al., 2009; de León & de León, 2019; Rico et al., 2020
	bar	-	5 - 15 litre/customer/day	10 litre/customer/day	Von Sperling, 2007
Institutional Place	school	pre-school	16.5 - 38.5 litre/student/day	26 litre/student/day	Farina et al., 2011; EPA statistics, 2012(a)
		high-levels	4.2 - 5.7 litre/capita/day	4.2 litre/capita/day	Garzón-Zúñiga & Buelna, 2011; Piroozfar et al., 2012
	hospital	-	174 - 580 litre/bed/day	464 litre/bed/day	Von Sperling, 2007; Mexican Institute of Water Technology Report, 2007; EPA statistics, 2012(c)
	clinic	-	0.92 - 2.62 litre/outpatient/day	1.77 litre/outpatient/day	Bahramian et al., 2016
	public toilet	-	10 - 25 litre/user/day	17 litre/user/day	Von Sperling, 2007
	municipality	-	15 - 30 litre/visitor/day	20 litre/visitor/day	Metcalf & Eddy, 1981
	museum/ library	-	15 - 30 litre/visitor/day	20 litre/visitor/day	Metcalf & Eddy, 1981

Table 2.4 Typical concentrations of TSS, BOD5 and COD in wastewater from different sources

ROOT ITEM	ITEM	SUB ITEM	TSS (mg/l)	BOD (mg/l)	COD (mg/l)	REFERENCE
Family Mill	ice cream	-	~ 265	~ 523	~ 11900	Qasim & Mane, 2013
	poultry processing	-	~ 1164	~ 1209	~ 4221	Bustillo-Lecompte et al., 2016
	cornflour	-	~ 650	~ 3000	~ 4850	Rajagopal et al., 2013
	snacks	-	~ 3200	~ 2600	~ 4700	Boguniewicz-Zablocka et al., 2020
	coffee	-	~ 2390	~ 8005	~ 17244	Rossmann et al., 2012; Tacias-Pascacio et al., 2019
	water bottling	-	~ 15	~ 50	~ 346	Ramirez Camperos et al., 2004
	textile	-	~ 52	~ 91	~ 1505	Somensi et al., 2010; Blanco et al., 2012
	leather	-	~ 1244	~ 977	~ 2533	Mandal et al., 2010
	wood	-	~ 106	~ 1724	~ 2740	Nasr et al., 2012
	blacksmithing	-	~ 345	~ 80	~ 360	Beh et al., 2012
	furniture (tile)	-	~ 21221	~ 266	~ 361	Abadi et al., 2016
Commercial Place	bakery	-	~ 140	~ 387	~ 812	Chen et al., 2004; Struk-Sokolowska & Tkaczuk, 2018
	restaurant	full-service	~ 257	~ 932	~ 1400	Lesikar et al., 2004; Murthy et al., 2007
		fastfood	~ 70	~ 560	~ 1360	Coronado et al., 2015
	hotel	-	~ 125	~ 70	~ 138	Pharmawati et al., 2018
	bar	-	~ 87	~ 161	~460	Gurd et al., 2019
Institutional Place	school	pre-school	~ 471	~ 203	~ 496	EPA statistics, 2012(a)
		high-levels	~ 120	~ 225	~ 423	Garzón-Zúñiga & Buelna, 2011
	hospital	-	~ 255	~ 603	~ 855	Gautam et al., 2007
	clinic	-	~ 893	~ 88.6	~ 196.8	Akporhonor & Asia, 2007
	public toilet	-	~ 37200	~ 6180	~ 26600	Nikiema et al., 2014
	municipality	-	~ 2260	~ 630	~ 940	Vinod & Mahalingegowda, 2014; Shivaranjani & Thomas, 2017
	museum/library	-	~ 2260	~ 630	~ 940	

Table 2.3 shows the information about the wastewater production per unit product in different types of places. For instance, wood industry generates 1442 litres wastewater for producing 1 m^3 wood-based panels, while cornflour industry generates 20 - 60 litres wastewater, typically 40 litres, for producing 1 kg flour. Different industry types have different units and different wastewater production per unit. The same rule also applies to commercial and institutional places. Table 2.4 lists the typical quality of wastewater from different provenances. For instance, the wastewater outflowing from a bakery normally contains TSS 140 mg/litre, BOD5 387 mg/litre and COD 812 mg/litre, whereas the concentrations of three indicators of the hospital wastewater which always varies with the use of medicines, but typically are 255 mg/litre, 603 mg/litre, and 855mg/litre, respectively. All figures are typical values of corresponding items and are found in literature. They function as initial values of according parameters in the model.

2.3 NETWORK-BASED ABM

Meanwhile, network-based ABM is widely developed in a wide range of studies. Zechman (2011) simulated the actions of utility manager agents and water consumer agents in response to a contamination event and the transport of the contaminant along with the water distribution network. Augustijn et al. (2016) built a network-based ABM to study the disease diffusion pattern with three kinds of agents: households, individuals, and rainparticles. The whole model consisted of a disease submodel (for simulating the two ways of disease generation: EH transmission and HEH transmission) and a hydrological submodel (for simulating the rainparticles' flow along rivers). Hilljegerdes & Augustijn-Beckers (2019) developed a prototype agent-based model to show the real-time movement of evacuees over a road network during two hurricane events and the damage to buildings and infrastructure caused by hurricanes. The network-based ABM of Wang et al. (2019) simulated the movement of shared automated vehicles in the city transport system to provide station-to-station service.

As part of the project the thesis belongs to, field data is planned to be collected in man holes of the sewage network in the future work, and we need to compare these values with predicted values to validate the model. Therefore, it is necessary to model the wastewater flow in the sewage network. For another, many research has shown that network-based ABM is a powerful tool to simulate the flow of agents in a network, so it could be practically workable to explore the effectiveness of such a method in simulating the wastewater generation and real-time transport in the sewage network.

2.4 ODD + D PROTOCOL

ODD (Overview, Design Concepts and Details) protocol is a standard protocol for describing ABMs, which has been developed and tested by a large number of modellers covering a wide range of application fields, especially the ecology field (Grimm et al., 2006; Grimm et al., 2010). It comprises three parts: first, the 'Overview' part gives an overall picture of the purpose and fundamental processes of the model; second, the 'Design Concepts' block depicts the general concepts underlying the model design; third, the 'Details' part provides more detailed and necessary information that allows for a reimplementation of the model (Koutiva, 2016). However, in the ABMs in social–ecological fields, core attention should be put on the human decision process, which cannot be sufficiently fulfilled within the ODD protocol (Polhill et al., 2008; Müller et al., 2013). Thus, a refined version: ODD + D protocol was developed and soon widely used to explain ABM in socio-ecological systems (Groeneveld et al., 2017; Schlüter et al., 2017). The composition of the "ODD + D" protocol is shown in Figure 2.2 which is the base of the explanation of the ABM in the thesis.

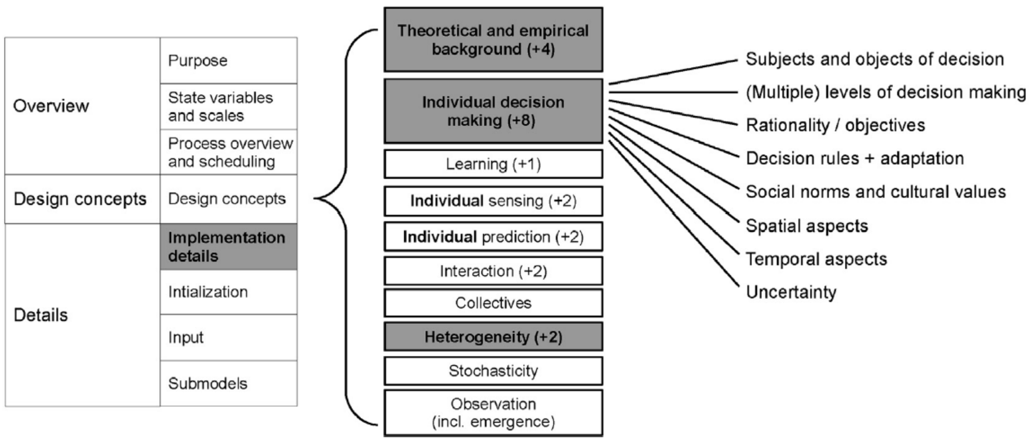


Figure 2.2: ODD + D Protocol (Source: Müller et al., 2013)

3 METHODOLOGY

This thesis develops an urban wastewater quantity and quality (UWWQQ) model based on agent-based modelling method to simulate the variation of the production and the composition of the wastewater generated in an urban system over time and space. The whole model comprises two sequential processes: the wastewater production process and the wastewater transport process, as shown in Figure 3.1. For the sake of simplification, plus considering the actual situation of the study area, two assumptions are made in the model design:

Assumption 1: the water quality and quantity in an urban environment only relates to the urban use of water, ignoring the agricultural water use and other water uses in rural areas.

Assumption 2: the wastewater quantity and quality in a city with a separated drainage system, as the case in the thesis, is only affected by human water use practices, ignoring the dilution effect of rainfall.

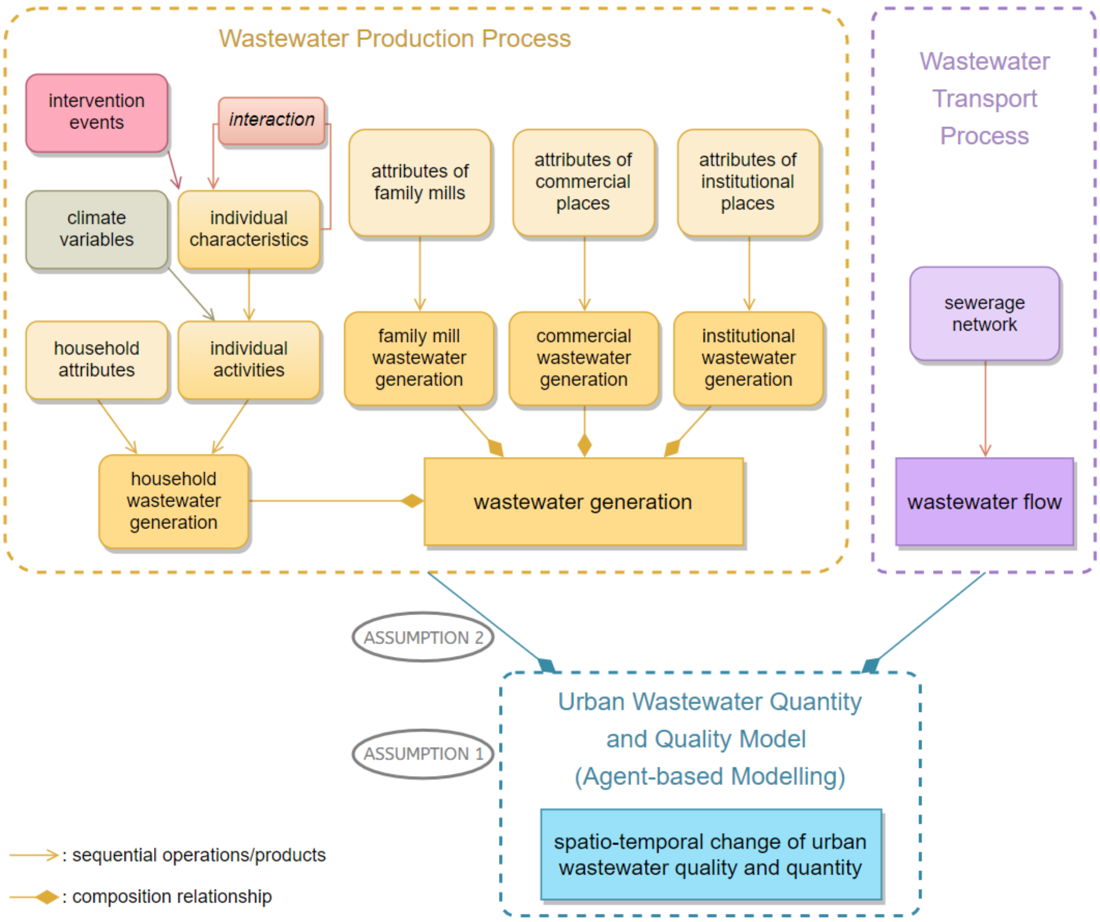


Figure 3.1 conceptual overview of the model

The wastewater production process depicts how and how much wastewater is generated from human behaviour in an urban system, including wastewater from households, industries, commercial places, and institutions (Von Sperling, 2007). However, there are no large-scale industries in the study area, but many family-based mills that serve for all kinds of local industrial activities, e.g., family lumber mill and family grain mill. Thus, industrial wastewater and its generation mechanism is conceptually supplanted by family mill wastewater generation, as shown in Figure 3.1.

Diversified influential factors and wastewater-generation mechanisms are designed in the production process to express different water-use scenes in real life. For instance, the wastewater production in a household depends on household attributes (e.g., household size) and family members' water use activities that are further decided by individual characteristics (e.g., age, employment status and water-saving consciousness) and climate conditions (e.g., precipitation and temperature). Among all these individual characteristics, water-saving consciousness is the only one that varies in time, since it is impacted by intervention events (e.g., a water-saving campaign held by government) and neighbours' water-saving consciousness. Contrarily, the wastewater of a family mill is dominated by the wastewater generated in its manufacturing process that depends on the attributes of the mill per se (e.g., the product type and scale) (Ranade & Bhandari, 2014). The same rule also applies to wastewater production processes in commercial and institutional places.

Subsequently, the wastewater transport process simulates the movement of wastewater along the sewerage network, from its provenance to its travel destination: a designated wastewater treatment plant (WWTP). Two modelling steps are involved: 1) to construct the sewerage network with geographical information made up by unidirectional sewer pipes across the city; 2) to determine the characteristics of wastewater flow, including the moving path consistent with the network and the moving velocity varying with pipelines.

These two processes occurring in sequence in real life are modelled within a single network-based ABM. The following description of the conceptual model adopts the framework of 'ODD + D' protocol, and a corresponding summary table is shown in Appendix I.

3.1 OVERVIEW

3.1.1 PURPOSE

The model is built to simulate wastewater production (quantity and composition and timing) and wastewater flow via the sewerage network to the treatment plant. It is designed for researchers to form a comprehensive picture of how the wastewater is generated and transported in a city, and for decision-makers to run scenarios to predict the effect of changing conditions (e.g., climate change) and intervention events (e.g., organising water-saving campaigns) on wastewater production.

3.1.2 ENTITIES AND STATE VARIABLES

The environment of the model, namely the activity space for all agents and collectives, is a digital representation of the actual scene of the study area: wastewater treatment plants, buildings unevenly distributed over the study area, including dwellings, family mills, and commercial and institutional establishments, as well as the sewerage network. As in Figure 3.2, each sewer pipe has, apart from its spatial location, state variables: *Direction*, *Slope*, *Material*, *Diameter* and *Velocity*. Besides, two global variables, also called exogenous factors, are included: *Precipitation* and *Temperature*. Both are climate factors having a disproportionate impact on human behavioural patterns. One extra environmental variable is *Campaign*, showing the status of the government organising a water-saving campaign or not.

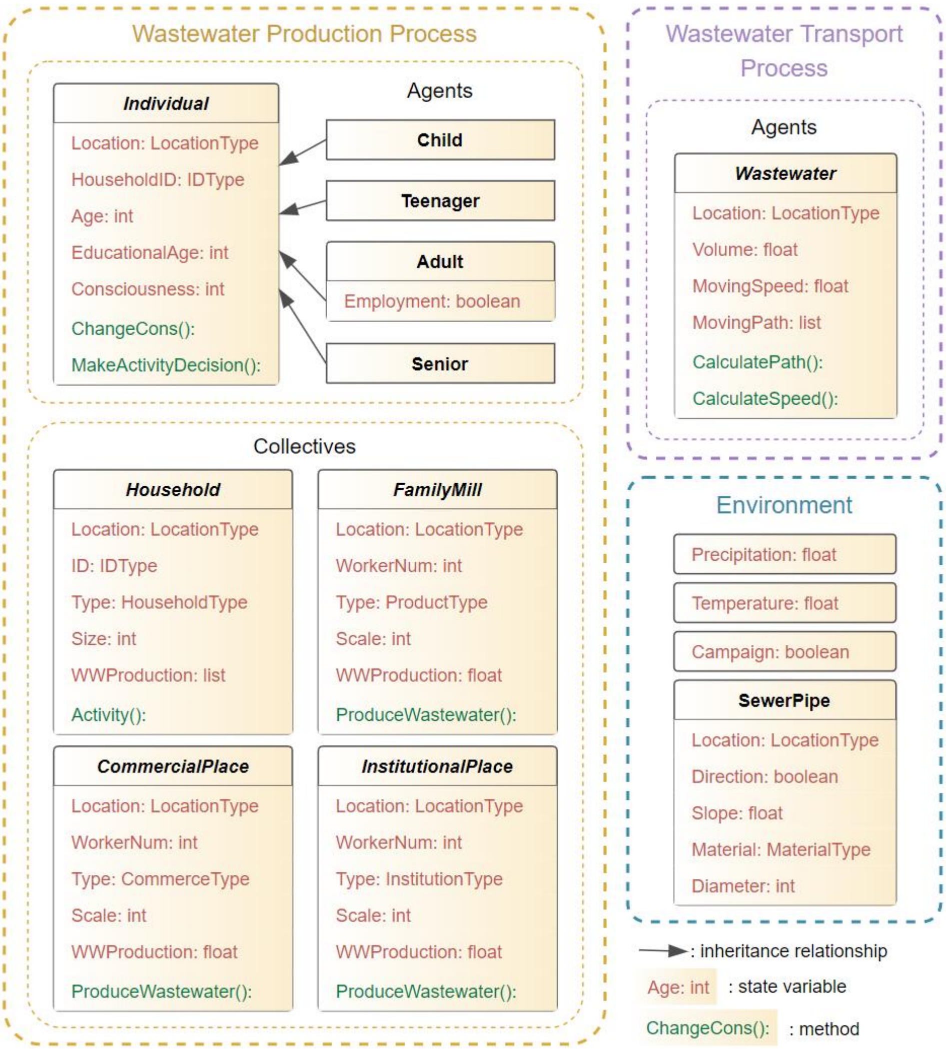


Figure 3.2 An overview of all elements in the ABM

Disparate agent types are created for different processes, as shown in Figure 3.2. In the wastewater transport process, only one agent type is created: wastewater (WW). Each WW agent refers to a wastewater particle of *Volume* which is consistent throughout the life of the agent. Besides, each agent moves to a new location at each time step based on its current location and other two state variables: *MovingPath* and *MovingSpeed* that are separately the results of its two methods: CalculatePath and CalculateSpeed. The former method is executed only when the agent is created, while the latter is executed at each time step until the agent dies. Both are elaborated in the *Submodels* section.

In the wastewater production process, there is also only one type of agent created: individual, reflecting real-life individuals. They are attributed with *Location*, *HouseholdID*, *Age*, *EducationalAge* and *Consciousness* variables. *Location* means that they are geo-referenced, either at home or in the workplace in simulation, which depends on the working hours. *HouseholdID* is the ID value of the household that the agent belongs to. *EducationalAge* refers to the years of an individual being educated, normally calculated from elementary school. *Consciousness* variable that shows individual water-saving consciousness level is the result of the agent's ChangeCons method that executes every day in simulation. MakeActivityDecision is a method that varies with individual, showing the mechanism how an individual makes decisions on conducting a water-use activity or not at a certain time. Both methods are clearly described in the *Submodels* section.

Because people at different age spectrums are characterised by disparate water-use patterns in real life, individual agents are divided by age into four subtypes: Child, Teenager, Adult and Senior. Adult agents are designed with one more state variable: *Employment*, showing if an adult has to go out for work or not on weekdays, which is used to determine which collective they will be part of at a specific time. Such division also has to do with initialising *Consciousness* values and responding to the water-saving campaign.

Different groups of individuals can form different collectives. The model considers four types of collectives: Household, FamilyMill, CommercialPlace and InstitutionalPlace. These collectives are connected by the movement of Adult agents with the *Employment* value of 1 who have to go out to work during working hours, and the movement of Teenager agents who go to school during schooling hours. When an employed adult is at home, it is part of the household collective, but when it is working, it becomes part of the family mill or commercial place or institutional place collective. Similarly, when teenagers are at school, they belong to the School collective (a subtype of institutional place collective), otherwise they are part of the household collective. These four collectives refer to the four kinds of real-world places respectively where urban wastewater is produced, so they are geo-referenced, with their locations in the digital environment in one–to–one correspondence with the locations of real-world buildings. Like agents, they are endowed with their own attributes and behaviour.

A household collective is made up of its family members (namely the agents with its *HouseholdID* value equalling to the collective's *ID* value.) who are at home. Household collectives also have other attributes: *Type*, *Size*, and *WWProduction*. *Type* defines the type of family, with options as 'single', 'young couple', 'retired couple', 'family with children' and 'family without children', while *Size* means the population of the family. *WWProduction* variable refers to the hourly wastewater production from the household. It is the result of a global function - Quantification method, with its expression as a list. Each element in the list represents the wastewater production via a specific type of domestic water-demanding devices, including the bathtub, the toilet, the washbasin, the shower, the kitchen sink, and the washing machine. Activity method of household collectives expresses their decision-making mechanism of if they use the kitchen sink for cooking or use the washing machine for washing clothes at a certain time.

The other types of collectives, i.e., FamilyMill, CommercialPlace and InstitutionalPlace, are formed only during their working hours by the group of individuals who work there. Apart from the spatial location, each type of these collectives has three additional state variables: *WorkerNum*, *Type*, *Scale* and *WWProduction*. Taking FamilyMill collective as an example, the four variables refer to the following attributes of the family mill respectively: the number of workers working there, the product type of the mill, the scale of the mill and the wastewater production by the mill's industrial process at each hour. The *WorkerNum* value is directly linked to the wastewater produced by workers' water-use activities, whilst the following two variables jointly determine the wastewater production during the mill's manufacturing process.

Type is a classification variable, with values of 'ice cream', 'poultry processing', 'cornflour', 'snacks', 'coffee', 'water bottling', 'textile', 'leather', 'wood', 'blacksmith' and 'furniture', while *Scale* answers how many products can be made in the mill in a day. The units for *Scale* have to be matched up with the *Type* of the mill, as listed in Table 2.3 in chapter 2, which mainly conforms with the expressions in the book of Von Sperling (2007). Then, each type of FamilyMill collective is endowed with its own ProduceWastewater method to calculate the wastewater production in its manufacturing process at each hour, and its calculation result is put into the *WWProduction* variable. Here, the method is assumed to be uniform for all mill types. Similar rule also applies to other two collective types, but the ProduceWastewater method of CommercialPlace or InstitutionalPlace collective varies with its *Type* values. Values of the *Type* attribute of CommercialPlace collective are 'bakery', 'restaurant', 'hotel' and 'bar', while such values of InstitutionalPlace collective are 'school', 'hospital', 'clinic', 'public toilet', 'municipality' and 'museum/library'.

3.1.3 SCALES

In terms of temporal resolution, each simulation run spans a whole year at hourly time steps. Except that *Temperature* and *Precipitation* variables update themselves every day and the individual ChangeCons method is executed at the beginning of the day (namely once every 24 time steps), as well as the WW agents' CalculatePath method is executed only once, other methods are run and corresponding variables are updated at each time step. As for the spatial resolution (spatial extent), the model covers only one catchment area, meaning that the wastewater produced by all types of water use in the study area coalesces into one wastewater treatment plant (WWTP). The sole treatment plant provides sanitation service for 726 families and 2815 locals, as well as around 80 family mills and about 250 commercial and institutional establishments all over the study area.

3.1.4 PROCESS OVERVIEW AND SCHEDULING

As explained before, the model comprises two processes: the wastewater production process and the wastewater transport process that are executed successively. The production process includes the wastewater generation from four provenances, corresponding to the four types of collectives: household, family mill, commercial and institutional place. Household wastewater is generated by individual activities and the collective's own behaviour, while the other three types share the similar production process that is dominated by behaviour of the collective itself.

The four categories are linked by Adult agents with employment value of 1. They are part of the household collective before going out to work, and then belong to the family mill or commercial place or institutional place collective when they are working, and finally become the household collective again after returning home. That is to say, they generate wastewater in family mills or commercial or institutional establishments in working hours, but produce household wastewater during off-hours. Procedures of different types of wastewater production processes and the procedure of the transport process are explained separately below.

Household wastewater generation procedure

Figure 3.3 shows the complete steps of household wastewater production (all methods mentioned below are elaborated in the *Submodels* section):

1) at the beginning of each day, climate factors, i.e., *Precipitation* and *Temperature*, update themselves, and individual agents recalculate their values of water conservation *Consciousness* variable via the ChangeCons method that considers the influence of neighbouring individuals and of the water-saving campaign if it is held. In the method, the type of the household collective that an individual belongs to has an impact on the definition of its neighbouring individuals.

2) at each single time step, all individuals at home make decisions on what water-use activities to do based on the MakeActivityDecision method. This method takes updated *Precipitation* and *Temperature* values as well as individual characteristics as inputs. Its

results are individual decisions on doing or not each of these activities, i.e., using the bathtub, the toilet, the washbasin, and the shower;

3) after individuals determined their activities, the household collectives will decide their activities of using the kitchen sink or the washing machine or none based on their Activity method. This method calculates the probability of a household collective doing an activity by considering some local customs., such as the average probability of eating outside for lunch and dinner, as well as the usual time slots for washing clothes.

4) the quantity and quality of wastewater produced by each type of individual activities and household collective's behaviour are calculated by the Quantification method that takes individual *Consciousness* and household *Size* into account. Afterwards, this method outputs a list concatenating the calculation results classified by device, namely the single wastewater production from the bathtub, the toilet, the washbasin, the shower, the kitchen sink, and the washing machine that is the total volume produced by all family members using the according device. The concatenation result is used to update the *WastewaterProduction* variable of the household collective. Finally, the exact content of each indicator (i.e., TSS, BOD5 and COD) used to assess the wastewater quality is calculated based on the production of the wastewater through each device and the literature figures indicating the common concentration of this indicator in wastewater from the corresponding device.

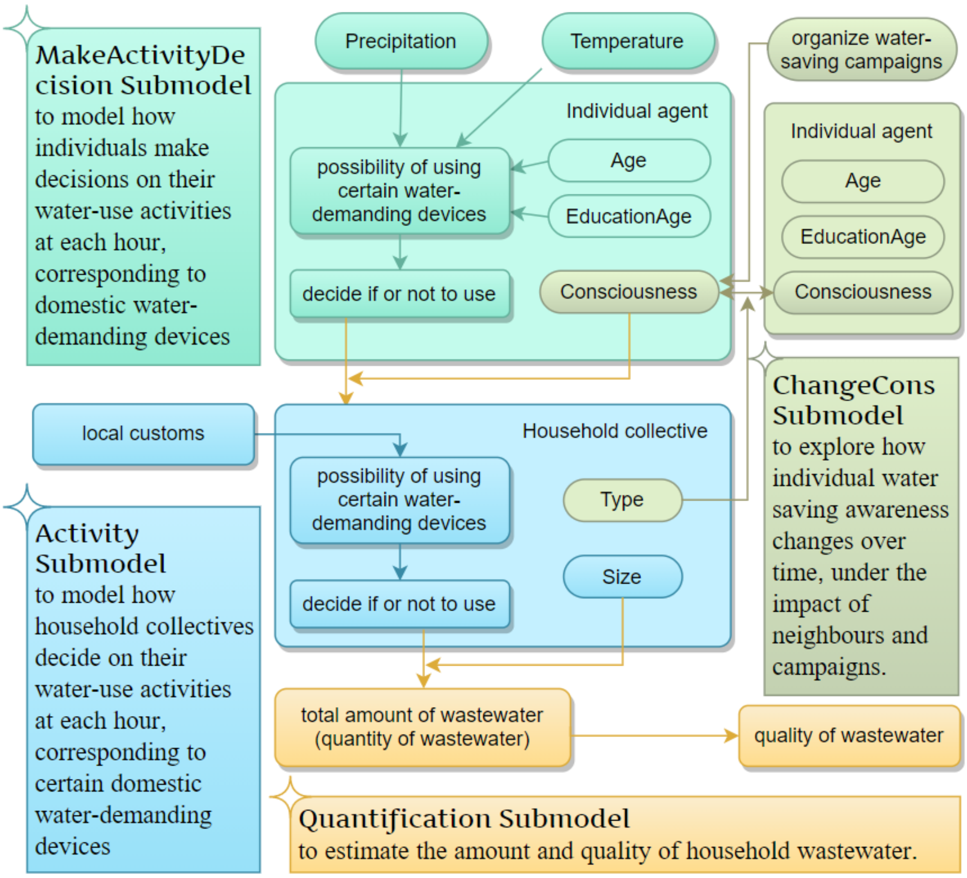


Figure 3.3: Household wastewater production process

Workplace wastewater generation procedure

The procedure of the wastewater generation of the other three types of collectives (i.e., FamilyMill, CommercialPlace and InstitutionalPlace) are quite similar, and utterly unlike that of the Household collective. Thus, the following description will take the FamilyMill collective as an example because the same procedure also applies to CommercialPlace and InstitutionalPlace collectives. The wastewater production from a FamilyMill collective is the sum of wastewater produced by its workers' daily water uses and by its manufacturing process. The former is a simplified version of the mechanism of Adult agents producing wastewater because only part of water-use activities is involved here, i.e., using the wash basin and the toilet, whereas the latter is only related to the product *Type* and *Scale* of the mill. In general, as shown in Figure 3.4, its wastewater production follows two steps (all methods mentioned below are elaborated in section *Submodels*):

1) at the beginning of each simulation run, every type of FamilyMill collective is created with a special wastewater production pattern. This pattern is decided only by the *Type* and *Scale* of the collective, depicting the change of the wastewater production in its manufacturing process over time;

2) at each single time step, workers of the mill produce wastewater following a simplified MakeActivityDecision method and the Quantification method. Meanwhile, the mill collective per se generates wastewater based on the ProduceWastewater method. The method takes the collective's attributes and wastewater production pattern as inputs and the amount and quality of wastewater produced in its manufacturing process as outputs that are put into the *WWProduction* variable of the collective. Therefore, the wastewater quantity and quality from the FamilyMill collective is the combination of the wastewater from the two sources.

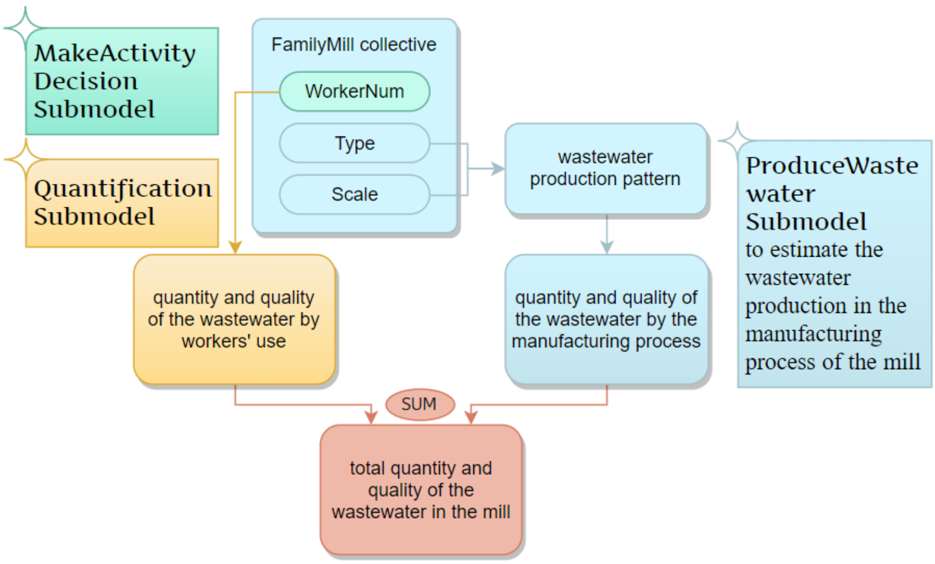


Figure 3.4: the wastewater production process of family mill collectives

Wastewater flow procedure

Subsequently, the wastewater transport process is executed, taking the outputs of the production process as its inputs. It simulates the flow of wastewater along the sewerage network towards its designated WWTPs, comprising two steps (taking a WW agent as an example, and all methods mentioned below are elaborated in section *Submodels*):

1) when a WW agent is created, it is initialised at the location of its provenance. For instance, if the agent is produced in a household, it will be initialised at the location of the household. Simultaneously, the *MovingPath* value of the agent is computed by the CalculatePath method that outputs the best/fastest path from its provenance to the WWTP based on environment information, e.g., the location of the WWTP and the properties of these unidirectional sewer pipes;

2) at each time step, the WW agent moves forward at the speed of its *MovingSpeed* value that will be updated by the CalculateSpeed method each time when the agent reaches a new node. The questions of how to make sure the WW agent moves exactly in conformity with its MovingPath in programming and how the CalculateSpeed method works are separately explained in the Movement submodel and CalculateSpeed submodel in the *Submodels* section.

3.2 DESIGN CONCEPTS

3.2.1 THEORETICAL AND EMPIRICAL BACKGROUND

This UWWQQ model is basically an empirical model as its conceptual framework is specially adapted to the circumstance of the study area and all parameter values in the model are calibrated by empirical data that are searched in literature. However, it also incorporates certain prevalent theoretical models in modelling. The first one is the Manning equation that forms the basis of the CalculateSpeed method that computes the velocity of wastewater agents flowing in pipelines. The second one is the synthetic generation method in the initialisation step. It is used to generate individual agents with personal characteristics (e.g., age and educational age) based on census data at the block level. It is worth noting that certain models that were involved in previous research are not included in the thesis, e.g., population dynamics and technological upgrades. This is because in a short-term (one-year) simulation, household members are assumed to be constant with no immigrants or migrants, and the categories of their water use practices are supposed to be unchanging with no new-tech devices invented to produce domestic wastewater.

In addition, the UWWQQ model is structured based on empirical information of the study area. First, individual water-use practices mentioned here refer to the practices that produce wastewater, and they are classified by device: bathtub, washbasin, toilet, shower, kitchen sink and washing machine. Garden is not included because gardening does not produce wastewater, and dishwasher and swimming pool are not considered either because few local families installed such devices. Moreover, individuals at different age spectrums are assigned with dissimilar water-use practices, which conforms with the real-life situation. Besides, industrial and socio-economic activities that produce wastewater in daily life are classified into three categories corresponding to collective's type: family mills, commercial and institutional establishments. This classification is based on existing workplace types in the study area where industry was replaced by family mills.

Finally, even the most comprehensive simulation model cannot include all elements of a phenomenon. Therefore, for the sake of simplicity and focusing on the main causality, some empirical assumptions are made at the system level:

- individual behavioural pattern is only determined by its own characteristics and influenced by climate factors.
- no biological or chemical reactions occur among the substances in wastewater from different sources.
- each wastewater agent follows its own path, with no physical conflict with other agents when moving.

3.2.2 INDIVIDUAL DECISION MAKING

In the model, only Individual agents and Household Collectives are endowed with the decision-making ability to decide if they do certain water-use activities at a certain moment. In terms of Individual agents, their decisions on water-use activities are made independently by the agent itself with no interference from other Individual agents, e.g., the decision to use the bathtub, the washbasin, the toilet, and the shower. Regarding Household collectives, they can decide independently and autonomously to conduct a water-use behaviour or not, e.g., the activity to use the kitchen sink and the washing machine. However, different decision-making mechanisms are designed for different activities.

For individuals' decisions to use the washbasin or toilet, they are all made only based on probability. Taking the activity of using the toilet as an example, each individual is assigned with a probability of using the toilet at each hour based on its water-use pattern, and then the individual randomly chooses a value between 0 and 1 at each hour. If the random value is smaller than the probability value at the same hour, the individual conducts the activity at the moment, otherwise not. By contrast, individuals decide to use the bathtub or shower in a more complicated way. They are designed with the memory capability, and when an individual is considering using or not the bathtub or shower, it has to recall if it has done that a few hours before. If yes, it will not do it again, otherwise it will follow the probability-comparison method, namely the decision-making mechanism of using the toilet. The series of decision-making mechanisms is realised by the MakeActivityDecision method particular for Individual agents.

One thing worth noting is that individuals can be classified by age into different subtypes: children, teenagers, adults, and seniors. Different subtypes are defined with different combinations of water-use practices, but for the same practice, they all follow the same decision-making rule. Besides, it is easy to notice that the probability value plays a big part in all decision-making rules. The basic value of the probability to use a water-demanding device at a certain hour is determined according to social norms and local culture, and is calibrated by empirical data from literatures. These basic values vary with the time of the day, with weekdays or weekends, and with the subtype of the individual. Meanwhile, actual probability values, the values of probabilities on a certain day, fluctuate based on basic values. They are also impacted by climate factors. High temperature and heavy precipitation can both contribute to high real probability values of using certain devices, e.g., the shower. The quantification of their relationships is embedded in the MakeActivityDecision method.

To make the decision-making process of Individual agents as similar as possible to the situation in real life, several assumptions are made in modelling for it and its subtypes:

- Individual agents are bounded rational, and their activities of water use are all reasonable, meaning that they use water only when they need to do so.
- All individual attributes remain constant during a single simulation, except the water-saving consciousness that changes when water-saving campaigns are held or when it is influenced by surrounding individuals' values.
- Teenagers have to obey the nine-year compulsory education and attend school from 8:00 to 18:00 on weekdays.
- Adults in employment follow the 9-to-5 schedule on weekdays, whereas on weekends, a minor part goes out for entertainment and others stay at home.
- Children, Adults out of employment, and Seniors stay at home all day on weekdays and part of them go out on weekends.

For Household collectives, they are designed with the decision-making ability to use the washing machine and the kitchen sink or not at any hour. The mechanism of them making decisions on using the washing machine or not is also the combined result of memory and probability. When a household collective is thinking of using the machine or not, it will check first if it has done the activity within a couple of days. If yes, the collective will not do it again, otherwise it will decide based on its probability value at the hour. However, if a household collective is thinking about using the kitchen sink or not (using the kitchen sink is regarded as only for making lunch or dinner at home in the model), it will at first decide if the family are about to eat out. If yes, it will not use it, otherwise the collective will follow the steps as that of deciding to use the washing machine. These mechanisms are involved in the Activity method, as the behaviour of Household collectives.

3.2.3 INDIVIDUAL SENSING AND INTERACTION

The sensing and interaction among various kinds of agents and the environment in the model are shown in Figure 3.5. The unique interaction is the one among Individual agents. Each Individual agent can sense the water-saving *Consciousness* values of other agents in its nearby households and then update its own *Consciousness* value based on such information. To be more accurate, if an individual sensed that most of the agents in its neighbouring and alike families have higher *Consciousness* values than itself, it would spontaneously raise its own value, otherwise it would keep this value unchanged. Such interaction is both geographically and socially local. Besides, individuals from the same family can mutually sense others' *Consciousness* value. If one family member has a higher value, other members of the family will improve their own *Consciousness* values to the same level. This type of sensing among Individuals is socially local, not geographically, because an Individual agent cannot sense such information of agents from other households. The changing mechanism of individual consciousness value is realised by the ChangeCons Method.

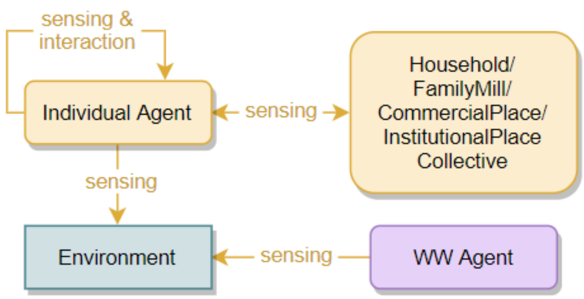


Figure 3.5: sensing and interaction in the model

Apart from the sensing and interaction among Individual agents, other types of sensing also exist in the model. The first one is between Individual agents and collectives. Any collective can directly sense the activities and states of its Individual agents, e.g., if an Individual agent is at home or at workplace and what water-use activities the agent is conducting. In turn, any individual can also sense the *Type* value of its household and other geographically neighbouring households, so that to demarcate its neighbouring individuals who should come from the same family type when updating its own *Consciousness* value. Such sensing is mutual and at the geographically local level. The second one is that Individual agents are able to sense the environment, namely the exogenous variables, i.e., *Precipitation* and *Temperature*. Such sensing is at the global level, that is to say, all Individual agents can sense the change of the climate condition at the same time, which does not vary with agents' spatial locations or personal attributes.

The third one is that WW agents can sense the environment as well. Instead of climate variables, WW agents are designed with the ability to sense the location of the WWTP, the geometry of the sewerage network, and the properties of sewer pipes. When a WW agent is created, all environment information is sensed to compute its *MovingPath* value. When the agent reaches a new node, it can sense certain properties of the pipe segment where it is to calculate its *MovingSpeed* value of flowing in the segment. This type of sensing is global, meaning that the environment information is sensed identically by all WW agents, no matter where they are and what attributes they have.

3.2.4 COLLECTIVES

There are four types of aggregations, i.e., Household, FamilyMill, CommericialPlace and InstitutionalPlace, that are formed by different groups of Individual agents. Each aggregation has a spatial location in the digital environment that is corresponding to the actual location of the building it represents. A Household collective is made up of its family members who are at home, while any collective of other three types is formed by Adult agents (a subtype of Individual agents) who are working there. Although all collectives are imposed in the model, the agents of each collective are always varying with time. For instance, a FamilyMill collective contains *WorkerNum* Adult agents there during working hours on weekdays, but none at other times. Only when there are agents in a collective, can it possibly produce wastewater. Each type of collective has its own attributes and behaviour, as explained in the last subchapter.

The four types of collectives are linked with each other by the movement of employed adults, namely the Adult agents with the *Employment* value of 1, and teenagers. An employed adult starts as part of a household collective at the beginning of the day, and then go out to work, belonging to a family mill or a commercial place or an institutional place during working hours (normally 9:00 am - 5:00 pm), and finally returns to the household collective again after finishing work and getting back home. Like employed adults, teenagers belong to the household collective at first, and then become part of the School collective (a subtype of the InstitutionalPlace collective) when they are at school on weekdays, and at last, return to their own households again after school.

3.2.5 HETEROGENEITY AND STOCHASTICITY

Heterogeneity exists in every type of agents and collectives in the model. For Individual agents, each variable value (i.e., *Location*, *HouseholdID*, *Age*, *EducationalAge* and *Consciousness*) changes with agent, and the behaviour (the decision-making rule) vary with the type of the individual with the parameter values in the rule depending on the agent itself, which is explained in the *Submodels* section. Compared to other types of individuals, Adult agents even have a special variable: *Employment*, whose value differs with the employment status of the agent: employed (1) and unemployed (0). In addition, WW agents are also characterised with heterogeneity. Such heterogeneity only exists in their state variables, rather than in their behaviour. They adopt the same behaviour, i.e., CalculatePath and CaldulatSpeed methods, but they are initialised at different locations and at different time. The former leads to a difference in their *MovingPath* values, while the latter has an impact on the instant *Location* and *MovingSpeed* values of the agents. The *Volume* value also varies with agent, depending on the volume of wastewater produced.

Meanwhile, heterogeneity can be found in all types of collectives. First, household collectives are heterogeneous in terms of the *Location*, *Size*, *Type* and *WWProduction* variables, as well as in their behaviour. Like Individual agents, the heterogeneity in state variables exists among different household objectives, while their behaviour differs based on the type of the household, but the parameters involved in defining behavioural patterns rely on the exact household's characteristics. Regarding other three types of collectives, all their state variables, i.e., *WorkerNum*, *Type* and *Scale*, are heterogenous for collectives of the same type. In terms of their behaviour, all subtypes of family collectives are assumed in the model to share the same behavioural pattern but with different parameter values, whereas CommercialPlace collectives or InstitutionalPlace collectives are designed with different behavioural patterns depending on the subtype of the collective.

On the other hand, stochasticity is involved in the decision-making mechanisms of Individual agents and Household collectives. The decision of an individual to conduct an activity at a certain moment is made based on its probability of conducting the activity at the moment, instead of determinate results - yes or no. Such activities include using the bathtub, the toilet, the washbasin, and the shower. Thus, even individuals with the same attributes may make distinct activity decisions in different simulation runs. Similarly, decision-making processes of household collectives using the kitchen sink and the washing machine also take in the stochasticity property. Detailed explanation of how stochasticity plays a role in the decisions of using water-use activities is already done in the last subchapter.

3.2.6 OBSERVATION

To provide a holistic understanding of the wastewater generation condition in the study area, a few observable scalar quantities are tracked when the ABM is running. Their values are recorded at each hour, so that at the end of each simulation run, several time series in one-to-one correspondence with the observations are plotted, respectively. Such observations include:

- the volume of the wastewater inflow to the WWTP; (primary)
- the quality (contents of TSS, BOD5, and COD) of the wastewater inflow to the WWTP; (primary)
- the total volume of wastewater all over the study area that remains in the pipe network;
- the average volume of wastewater produced by a single household;
- the average volume of wastewater produced by an individual from different types of households;
- the average volume of household wastewater produced by each water-use practice and their comparison;
- the average volume of wastewater produced by each water-use type, i.e., the water-use of households, family mills, as well as commercial and institutional establishments, and their comparison;
- the time series of the average *Consciousness* value of all Individual agents.

Besides, to simplify the visualisation of wastewater production in both quantity and quality over time and space, a 2D interface is designed to show the spatial distribution of these agents that changes over time. For any single WW agent, the sequence that concatenates its dynamic positions shows its trajectory from the provenance to the WWTP along the sewerage network. If time goes very fast, the movements of all WW agents will form the effect of a continuous wastewater flow at the aggregative level.

3.3 DETAILS

3.3.1 IMPLEMENTATION DETAILS

The whole model is built in the Netlogo platform version 3.4. One tick represents one hour, and the time frame for a single simulation run is one year, namely 8760 ticks.

3.3.2 INITIALISATION

As the preparation step of running a simulation, the initialisation of the model involves four parts: the initialisation of the environment, four types of collectives, Individual agents, as well as WW agents.

Initialisation of the environment

The initialisation of the environment means to build a digital environment simulating the actual environment of the study area. It functions as the background of all agents' and collectives' behaviour, demarcating their activity space. The environment is made up of several elements: residential blocks, households, buildings for industrial and socio-economic activities, drains and sewer pipelines, and wastewater treatment plants. Each object in the environment, e.g., a block or a building or a drain, is located at a fixed position with a specific shape and area. Besides the location and geometry information, some elements are also characterised by their own attributes. For instance, a residential block has such attributes as the number of the population at different age spectrums in the block and the average education age of the population, while the building for economic activities has the information of the building type and scale as well as the number of workers working there, and a sewer pipeline has its own technical parameters, i.e., length, diameter, and material, as well as the elevation of its starting point and end point that are used to determine the flow direction.

Initialisation of household and other collectives

Next, collectives of the four types, i.e., Household, FamilyMill, CommercialPlace, and InstitutionalPlace, are created based on the location information of various buildings in the environment. Each of the collectives is initialised at a specific location and no longer moves during the simulation, and meanwhile all of its attribute values are initialised based on the attributes of its simulated object. For instance, Household collectives are all in one-to-one correspondence with the household objects in the environment. The location of any Household collective is the same as its corresponding household object, and its *WWProduction* value is initialised as 0. Similarly, one-to-one correspondence also exists between FamilyMill collectives and the buildings that are family mills. Each FamilyMill collective has a fixed location and attribute values (i.e., building type, scale, and the number of workers) as exactly the same as its corresponding family mill object. The initialisation of CommercialPlace and InstitutionalPlace collectives is the same as that of FamilyMill collectives.

Initialisation of Individual agents – synthetic population generation

Subsequently, Individual agents are initialised via the synthetic population generation method based on the attribute values of residential block objects that reflect the census data at the block level. Block by block, individuals are created for each household with all attribute values initialised. This method contains seven steps, taking a residential block as an example:

1) Generate Individual agents with their ages randomly assigned, making the population at each age spectrum matching the census data of the block;
2) Classify Individual agents based on their age into Child (0-5), Teenager (4-14), Adult (15-59) and Senior (60-);
3) Preset water-saving consciousness values for all Individual agents: Teenagers'

values are set to be 1.1, while others are with the value of 1, considering that teenagers generally have a high-level water-saving awareness;

4) Calculate the *EducationalAge* value for each Individual agent based on its *Age*. Their relationship is shown in Table 3.1, implying the following requirements of the local education system:
    - People have to start schooling at 6;
    - Everyone has to fulfil the nine-year compulsory education;

Table 3.1: The relationship between individual Age and EducationalAge

For Individuals		
Age		**School Age (Education)**
0 - 14	0 - 6	0
	7 - 14	age - 6
15 - 29	15 - 22	9 (drop out) or age - 6 (not drop out)
	23 - 29	a random number from 9 to 16
30 - 59	30 - 59	a random number from 9 to 16
60 -	60 -	a random number from 9 to 16

5) Modify individuals' *EducationalAge* values to fit the average schooling value of the block;
6) Assign only one master (either an Adult or a Senior) to each household within the block based on their *Age* value ('assign' here means to move the Individual agent to the location of the Household agent, and put the *ID* value of the latter to the *HouseholdID* variable of the former);
7) Randomly assign those unassigned individuals to any household in the block.

After executing the method, all individuals have been initialised with *HouseholdID*, *Age*, *EducationalAge* and *Consciousenss* values and have moved to the location of their own households. It is worth noting that Individual agents created by the method may vary slightly and randomly in different simulation runs, but their information is totally consistent with the census data at the block level. Besides, when an Individual agent is created, it is instantly classified as Child, Teenager, Adult or Senior subtype. For Adult agents, the rate of those whose *Employment* value equal to 0 is consistent with the unemployment rate of the local labour market, and these unemployed Adult agents are selected randomly from the total Adult population. Meanwhile, after allocating all individuals in the block to households, the *Size* and *Type* values of each Household collective are also initialised.

Initialisation of WW agents

Finally, the initialisation of WW agents is always conducted when the simulation is running. When a new WW agent is created, it is initialised at the location where it is produced, with its *Volume* set as the volume of wastewater produced by the according collective at the moment and its *MovingPath* calculated via the CalculatePath method as well as its *MovingSpeed* preset to be 1 m/s. Besides, the volume of wastewater inflow to the WWTP is set as 0 at the beginning of each simulation run.

3.3.3 INPUT

Apart from the information used in the initialisation step, other inputs are also required by the model. The first input is the time series of climate variables: *Precipitation* and *Temperature*. They are stored in .xslx format and can be directly read in Netlogo. The second one is the value of parameters that are of great significance in the model. These values, depending on the research area, never change during a single simulation run, and are combined results of literature review and an analysis of the typical local lifestyle.

3.3.4 SUBMODELS

1. ChangeCons submodel

Individual water-saving consciousness plays an important role in the quantification process for household wastewater. The submodel is built to calculate the *Consciousness* value for all individual agents, laying the foundation for other submodels. It primarily embodies the impact of government measures, i.e., organise water-saving campaigns, and neighbouring environment on household wastewater production via raising individual water-saving consciousness. Based on previous literature, the increase of individual water-saving consciousness can be triggered by such intervention actions taken by the government (Darbandsari et al., 2017). Besides, the consciousness value of an individual agent living in household *H* can be impacted by individual agents that live in its neighbouring households U(*H*) (Galán et al., 2009). Finally, an illustration of updating individual water-saving consciousness is shown in Figure 3.6, considering three more assumptions that conform with real-life situations:

- a) individuals in the same household share the same *Consciousness* value that is the highest one among all family members' (so that if the term 'the household/ family consciousness' appears in the following description, it means the same *Consciousness* value shared by its family members.);
- b) with no influence from other individuals or intervention measures, the *Consciousness* value of every individual will decrease by 1% every day if its current value is higher than its initial value (1.1 for teenagers and 1.0 for others), otherwise remain the same;
- c) the *Consciousness* variable has an upper threshold and a lower threshold. Anyone who reaches the maximum *Consciousness* value will no longer increase its value when calculating, and vice versa.

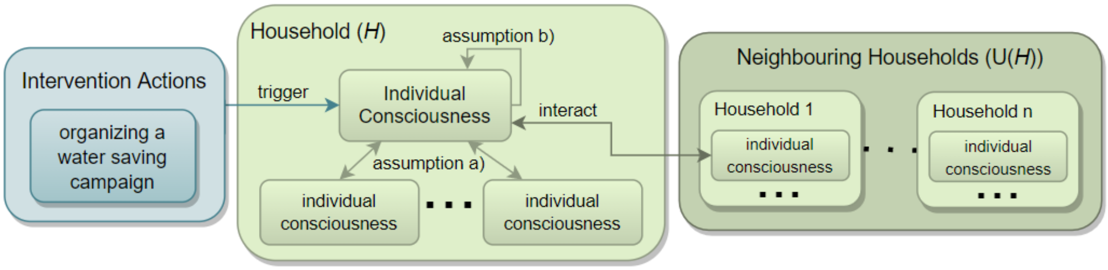


Figure 3.6: the mechanism of updating individual water-saving consciousness

The influence of intervention actions and neighbouring individuals on individual water-saving consciousness is computed by equation (3.1) in the thesis, similar to the research of Linkola et al (2013), where *a* means the influence of a water-saving campaign and *b* the impact of social interactions with neighbouring agents. The value of *MAX* refers to the upper limit of *Consciousness* variable.

$$Consciousness = \begin{cases} Consciousness + a + b, if\ Consciousness + a + b < MAX \\ MAX, otherwise \end{cases} \quad (3.1)$$

On the other hand, the intervention action and social interaction have disproportionate impacts on individual consciousness. First, the water-saving campaigns considered in the thesis are all assumed to be local campaigns, meaning that the influence extent of such a campaign is at the block level or at a local level (e.g., a school). That is to say, only individuals belonging to the block or the school where the campaign is organised can disproportionately enhance their *Consciousness* values. Furthermore, individuals with high *EducationalAge* are more likely to learn from others and the environment (Yuan et al., 2014), thus more influenced by the idea of saving water than those with lower education levels, which is simply expressed by equation (3.2). A water-saving campaign is assumed to take effect immediately after organising (Kang et al., 2012).

$$a = \begin{cases} 0,\ \ if\ there\ is\ no\ campaigns\ for\ saving\ water \\ 0, if\ there\ is\ a\ campaign\ and\ individual\ education\ age < 1 \\ 0.03, if\ there\ is\ a\ campaign\ and\ 1 \leq indivdual\ education\ age \leq 9 \\ 0.05, if\ there\ is\ a\ campaign\ and\ 9 < individual\ education\ age < 16 \\ 0.1, if\ there\ is\ a\ campaign\ and\ individual\ education\ age \geq 16 \end{cases} \quad (3.2)$$

Then, regarding the influence of social network, the *Consciousness* value of individuals in a household can only be impacted by individuals from nearby households. Here, ‘nearby’ has two meanings: proximity in both geographical (within a limited distance) and social (similar household types) distances (Koutiva & Makropoulos, 2016). That is to say, households of the same type and living a short distance away have a strong and easy communication, thus their consciousness interacts with each other frequently. In the conceptual model, the geographical distance threshold for close households is set as a parameter and its value can be determined according to the actual situation about people’s communication in the study area. Meanwhile, close social distance refers to sharing the same family type. Finally, the calculation equation adopted in the thesis is a simplified version of the diffusion model of Edwards et al. (2005). As shown in equation '3.3), the choice of an individual to either increase its *Consciousness* value or remain the same depends on the proportion of its nearby households with higher *Consciousness* values accounting for its total nearby households. This value is updated every day, because of the high frequency of such social interaction.

$$b = \begin{cases} 0, \\ (if\ the\ proportion\ of\ nearby\ families\ with\ higher\ consciousness\ values < 50\%) \\ \\ the\ mean\ of\ all\ its\ nearby\ families\ with\ higher\ values - its\ current\ value, \\ (\ if\ the\ proportion\ of\ nearby\ families\ with\ higher\ consciousness\ values \geq 50\%) \end{cases} \tag{3.3}$$

2. MakeActivityDecision submodel

This submodel works only for Individual agents, simulating the process of an agent making decisions on its hourly water-use practices. As stated before, Individual agents are classified into four subtypes by age: Child, Teenager, Adult, and Senior. Agents of different subtypes are endowed with distinct water-use patterns and decision-making processes. The submodel designs dissimilar water-use behaviour and models different decision-making processes for children, teenagers, adults, and seniors. The inputs of the submodel are individual characteristics and global parameters (e.g., *Precipitation* and *Temperature*), and the outputs are agents' decisions on doing certain activities or not at the current moment.

At first, different subtypes have their own combinations of water-use practices, because people's capability and responsibility vary largely with their age spectrums. Domestic water-use practices that can produce wastewater are differentiated by household water-demanding devices: bathtub, washbasin, toilet, shower, kitchen sink, and washing machine. The last two practices are the behaviour of Household collectives, while individual water-use practices are actually their activities of using the first four devices. Individual subtypes and their corresponding activities are connected by arrows, see Figure 3.7. Children under 6 are assumed to take a bath instead of a shower and use the washbasin to clean bodies, as well as to use the toilet. Teenagers (6 -14) and adults (15 - 59) are able to use all the four devices: the bathtub, the washbasin, the toilet, and the shower. Seniors (60 -) use all devices except the bathtub, because baths are mostly taken in houses of young couples and families with young children (Stewart et al., 2009).

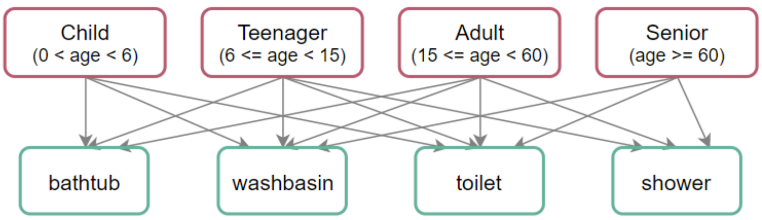


Figure 3.7: individual subtypes and their wastewater-generation practices

Then, at the beginning of each simulation run, the agents of each subtype are given the same probabilities of using these appliances at any time step, but there is a big difference among the probability values of different subtypes. Actually, the probability of using an appliance by an agent means the frequency of the agent using that appliance. In general, children are likely to use the bathtub and the washbasin more frequently than other subtypes as they are less careful about and more vulnerable to their surrounding circumstance. Teenagers are assumed to spend most of their time at studying so that their usage of all appliances is a bit lower than others on weekdays. Adults who work outside the home use the shower more times, because they have a stricter requirement for cleanliness. Seniors are natural to use the toilet more often, and they are assumed to take the shower less frequently.

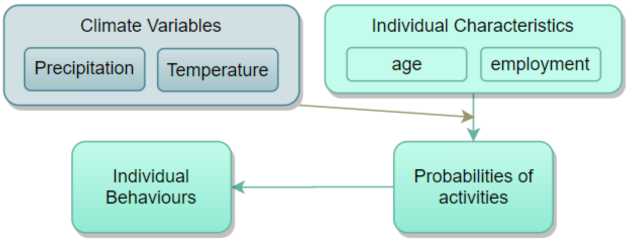


Figure 3.8: influence of climate and individual characteristics on individual behaviour

Furthermore, the probability values of certain practices are also influenced by climate condition, thereby impacting individuals' behaviour/decisions, as illustrated in Figure 3.8. The research of Cardell-Oliver et al. (2016) showed that there is a statistically significant relationship between the mean daily water demand per household and the mean daily temperature, that is, the average of the daily minimum and maximum temperatures. The demand is nearly linearly linked to the temperature, and such linear relationship is influenced by if the day is rainy or not because the demand is generally higher on no-rain days than that of rainy days. Likewise, the relationship between the probability of an individual conducting a certain water-use practice and the temperature is designed to be linear in the model, meaning that such probability increases with the temperature going up at a constant rate. Meanwhile, the precipitation determines if the day is rainy or no-rain, which decides the parameter values in the relationship between the activity probability and the temperature. In this way, their joint influence on any activity probability can be commonly expressed by equation 3.4, where a_1 is smaller than a_2 and b1 is near to b2, and their exact values vary with the exact water-use practice.

$$probability = \begin{cases} a_1 * temperature + b_1, if\ precipitation > 0 \\ a_2 * temperature + b_2, otherwise \end{cases} \tag{3.4}$$

Finally, every single agent will decide if it conducts or not the activities that it can do at the current moment. When an agent is deciding on a specific water-use practice, it follows the same decision-making mechanism explained in the last subchapter, but agents of different subtypes need to make decisions on their own combinations of these practices, following the unique sequence of decision-making actions (decision-making rule), as illustrated in Figure 3.9. At each tick, children make decisions on if they use or not the washbasin, the bathtub, and the toilet in sequence, while adults have to decide if they use or not all their possible devices one by one. A detailed illustration of the complete process of an individual making decisions on all its activities is presented in Figure 3.10, taking an adult agent as an example.

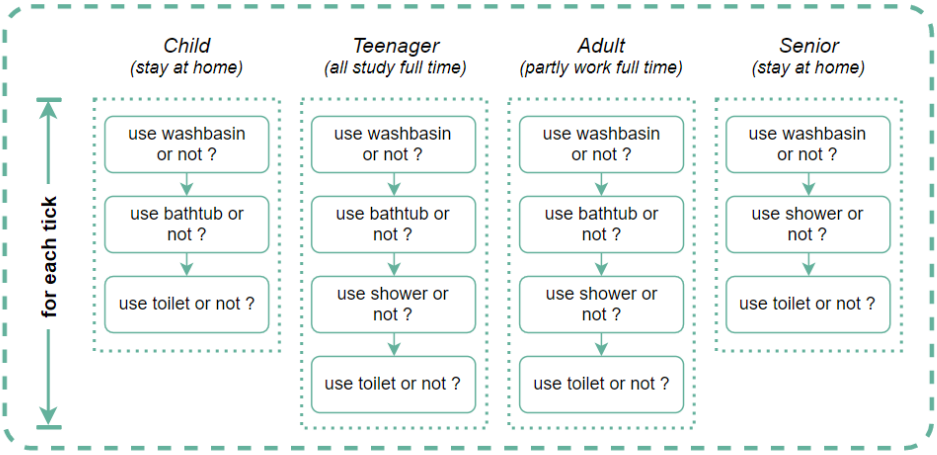


Figure 3.9: different decision-making rules for different agent types

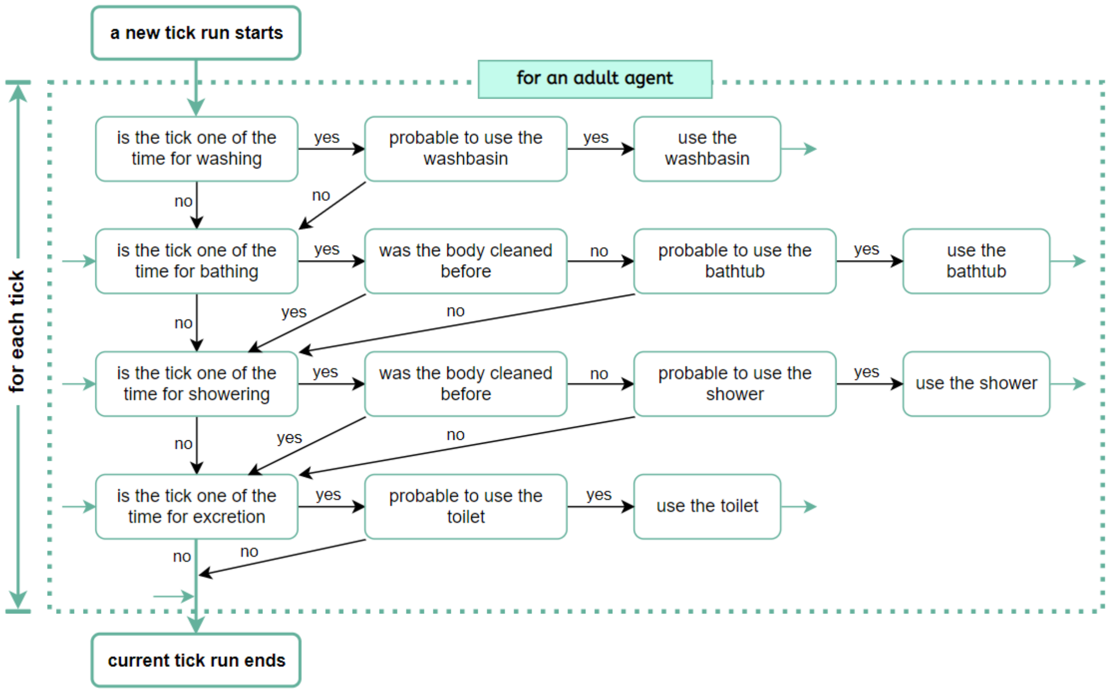


Figure 3.10: the complete decision-making process in modelling (of an adult agent)

In addition, the household wastewater production is also directly related to the at-home status of individuals. On weekdays, teenager and adults in employment have to go to school or work, while children, adults out of employment and seniors are not supposed to do so. On weekends, a small percentage of local families are presumed to go out for entertainment, while other families are assumed to stay at home. When individuals are outside home, their probabilities of using any device are set to be 0.

3. Activity submodel

The submodel defines the decision-making behaviour of household collectives on using the kitchen sink and the washing machine. It is worth noting that the use of kitchen sink here only refers to the activities of cooking (lunch or dinner) and cleaning dishes after meal, while the use of washing machine means the activity of washing clothes. Both activities are believed to be done for the entire family at fixed time slots. For instance, lunches are made normally between 12 and 13, and dinners commonly between 18 and 19. Washing clothes is mostly done at weekends, but for certain types of families (e.g., families with children or families with 4 or more members), they can use the machine one more time either on weekdays or weekends. Besides, the activity of washing clothes is supposed to be done only in the daytime. The detailed decision-making rule that is made up of a series of mechanisms of making decisions on using each device is shown in Figure 3.11.

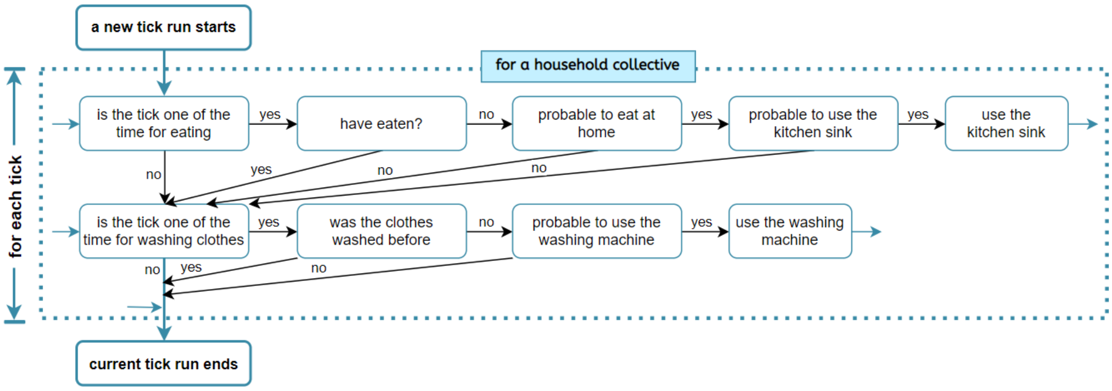


Figure 3.11: the complete decision-making process in modelling (of a household collective)

4. Quantification submodel

This submodel works only for Household collective type to calculate its *WWProduction* values at every single tick. The *WWProduction* variable updates its value at each hour, and the value is expressed as a list with six figures, each figure showing the volume of wastewater through a certain domestic device at the moment. The wastewater volume through a device is exactly the amount of wastewater produced by all family members using the device. Furthermore, the wastewater production of an activity depends on both the type of the device and the type of people who uses it (Makki et al., 2015). Thus, it is necessary to determine at first how much wastewater is produced by each single water-use activity, which may vary significantly with the individual subtype and characteristics as well as the household attributes.

The wastewater production of using a certain device once is basically determined by the type of user and fluctuates based on the user's water-saving consciousness, which is based on the research of Jin et al., (2014) that the increase of individual water-saving consciousness can influence the behaviour of washing activities more largely than flushing the toilet. For the activity of using the bathtub, if a child uses the bathtub, it will produce only half of the volume produced by an adult or a teenager using it. This value is supposed to have nothing to do with the individual water-saving consciousness. In terms of the other water-use activities of Individual agents (i.e., using the washbasin, the toilet, and the shower), the basic volume (litre) of using a certain device once is presumed to be the same for all individuals, but the real volume (litre) in calculation for an individual is the result of the basic value impacted by the individual's water conservation awareness. Such impact follows an approximate inverse sigmoid curve, as shown in Figure 3.12 and expressed by equation 3.5 where a (< 1) and b (> 0) are both parameters, which copies the law of diminishing marginal utility in economics. That is to say, once beyond the average value (1.0), the effect of increasing the consciousness on reducing the wastewater production will decrease with the continuing rise in consciousness, and vice versa.

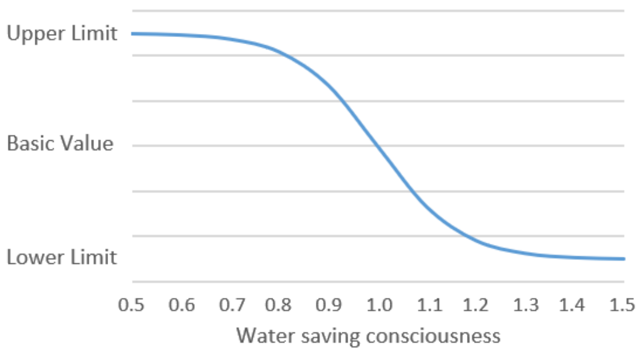


Figure 3.12: the inverse sigmoid curve used to approximate the impact of temperature

$$real\_volume = basic\_volume * a/(1 + e^{b*(Consciousness-1)}) + basic\_volume * (1 - a/2) \quad (3.5)$$

In terms of household collectives' behaviour, the quantification processes of the two activities are totally disparate. The quantification of wastewater from using the washing machine once is similar to that of using the shower. The basic value of its unit wastewater production is determined by technical parameters of the machine, and the relationship between the production and the household consciousness (the highest *Consciousness* value of individuals in the household) also follows the inverse sigmoid function, like equation 3.5. On the contrary, to quantify the wastewater from using the kitchen sink once by a household, including the wastewater from cooking a meal and cleaning dishes after meal, a constant is introduced to refer to the basic value of the wastewater production for one person. The constant is assumed to be equal for all subtypes of individuals and its real value in calculation does not vary with individual water-saving consciousness. In this way, the amount of wastewater by using the kitchen sink once is proportionate to the number of people who are at home, often the household size, as shown in equation (3.6), where the $volume\_kitchen\_sink$ (litre) means the total volume of wastewater produced by using the kitchen sink once at the household level.

$$volume\_kitchen\_sink = volume\_kitchen\_sink\_per\_person * population\_at\_home \quad (3.6)$$

After determining the wastewater quantity of each water-use activity, three kinds of potential outputs can be generated at last according to different objectives. The first one is to measure merely the total quantity of wastewater. It is the amount of a household's wastewater at a single tick, which is the sum of the wastewater produced by all activities. It can be expressed by equation 3.7 where WP means the total wastewater production of a household collective at a single tick, while $WWProduction_i$ refers to the wastewater production of the ith activity in the household, namely the ith figure in the list. $i = 1,2,3,4,5,6$ respectively refers to the activity of using the bathtub, washbasin, toilet, shower, kitchen sink, and washing machine. The unit of all following equations is litre.

$$WP = \sum_{i=activity} WWProduction_i\,,\ i = 1,2,3,4,5,6 \quad (3.7)$$

The second potential output is the volume of wastewater produced by a certain activity within a household. It aims to measure the household wastewater production from different water-use devices, and the calculation expression is shown in equation (3.8). WP_i means the volume of wastewater produced by the ith activity conducted by either Individual agents or Household collectives.

$$WP_i = WWProduction_i,\ i = 1,2,3,4,5,6 \quad (3.8)$$

The third potential output is the quality of wastewater at the household level, including a few prevalent water quality indicators, i.e., total suspended solids (TSS), five-day biological oxygen demand (BOD5) and chemical oxygen demand (COD). The content of TSS in household wastewater can be roughly calculated by equation 3.9. tss_i means the content of TSS in the wastewater generated by the ith activity. Apart from TSS, the calculation of other two indexes are expressed by equation 3.10 and 3.11, respectively, following the same principle as calculating TSS content.

$$TSS = \sum_{i=activity}(tss_i * WWProduction_i)\,,\ i = 1,2,3,4,5,6 \quad (3.9)$$
$$BOD\_5 = \sum_{i=activity}(bod\_5_i * WWProduction_i)\,,\ i = 1,2,3,4,5,6 \quad (3.10)$$
$$COD = \sum_{i=activity}(cod_i * WWProduction_i)\,,\ i = 1,2,3,4,5,6 \quad (3.11)$$

These three kinds of outputs make sense for different purposes. The total amount of wastewater can give an overview of how much wastewater will be generated at what time. This information can help the government design the size of sewer pipes and the capacity of the treatment plant as well as optimising the sewerage network. The volume of wastewater through each domestic device can provide such information as what activity contributes the most to the total volume, which can help make targeted policies to reduce the wastewater production. The contents of wastewater quality indicators give a clear and concrete picture of the composition of wastewater produced, so that the function of the wastewater treatment plant can be better designed or upgraded, targeting the substances with the highest contents or that can cause the most harmful consequence.

5. ProduceWastewater submodel

The submodel aims to quantify the wastewater produced by diverse industrial and socio-economic activities that are conducted by FamilyMill, CommercialPlace and InstitutionalPlace collectives. The wastewater-generation processes of the three types of collectives are quite similar, so the following description will take the FamilyMill collective type as the example. This submodel can estimate the quantity and quality of wastewater produced in the industrial process of FamilyMill collectives. All family mills are assumed to have the same wastewater production pattern that shows the general trend of the volume of wastewater produced in the manufacturing process of a mill. The pattern only shows the relative values, namely the portions of the hourly wastewater production accounting for the daily amount. When the model is running, the hourly absolute values will be calculated by multiplying the relative values and the daily amount for each mill. Exact patterns and daily amounts are ascertained from literature and the mill's properties. In this way, the wastewater production of family mills at each hour is determined with little stochasticity. The same rule also applies to Comme'cialPlace and InstitutionalPlace collectives.

Then, considering that the composition of wastewater varies considerably with the type of economic activities, the wastewater quality (i.e., the concentrations of TSS, BOD5 and COD) at each collective is obtained by consulting literature, and the result is shown in Chapter 2.

6. CalculateSpeed submodel

This submodel aims to calculate the moving speed of WW agents in pipes as accurate as possible. For this purpose, Manning's equation is adopted as the basic formula of computation, because it is exactly the formula that is used in the technical specification of blueprints for rehabilitating the sewage pipes in the study area. The Manning formula is the most widely used equation for estimating the average velocity of a liquid flowing in a uniform open channel (Hager, 2006). It also applies to conduits flowing part full, for they possess a free surface like that of open channel flow (Barr et al, 1986). All flows in these channels are driven by gravity (Manning formula, 2021), which is exactly the case in research. The Manning equation with a coefficient *K* is defined by equation (3.12) and its related equation is in equation (3.13) (Akgiray, 2005):

$$V = \frac{K \cdot {R_h}^{2/3} \cdot S^{1/2}}{n} \tag{3.12}$$

$$R_h = \frac{D}{4}\left(\frac{\theta - \sin\theta}{\theta}\right) \tag{3.13}$$

Where V is the mean flow velocity (m/s), R_h is the hydraulic radius (cross-section area divided by wetted perimeter) (m), S is the mean slope of the channel (m/m), n is the Manning roughness coefficient (namely surface roughness that is based upon channel material and condition), K is a constant dependent upon units, D is the diameter of the uniform channel, and θ is the central angle of the flow surface. An illustration of all these parameters is shown in Figure 3.13.

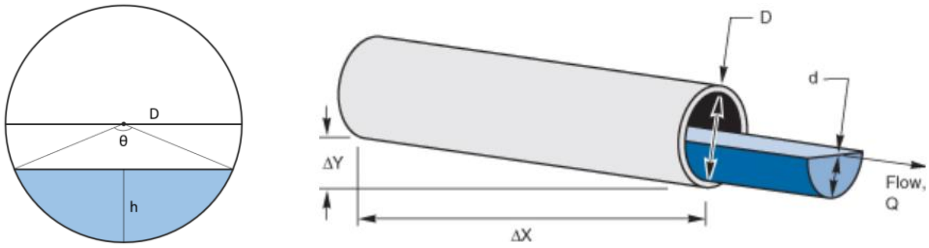


Figure 3.13: the illustration of the equation's parameters (source: Manning formula, 2020)

The value of K can be directly calculated by the inverse function of equation 3.15, based on the minimum and the maximum velocities in the system that are respectively 0.6 m/s and 3.0 m/s. After iterative computations, K is worked out to be 0.016212. Finally, the flow velocity of WW agents in each pipe segment can be calculated based on these two equations, and for simplicity's sake, two assumptions are made:

- the value of θ is determined by the instant flow rate, and here it is set as a constant: 180°, namely π (in radians)
- the value of n is only decided by the material of the channel that is plastic in the case. According to the Manning's roughness coefficient table (Manning roughness, 2021), the value of n is 0.009.

7. Movement submodel

After executing the global function: CalculatePath method that calculates the shortest path from one point to another, the moving path of each WW agent to the WWTP is determined. The pipelines are all unidirectional and their directions conform with the local topography, so the moving path is the unique possible path from the WW agent's current location to the WWTP. That is to say, at each intersection in the pipe network, all WW agents have only one way to go. Taking a WW agent as an example, how it moves along its path is illustrated in Figure 3.14. The pipelines are actually line data in implementation, but to make the illustration intuitive and intelligible, the pipelines in Figure 3.14 are represented by rectangles.

When the WW_i agent reaches Node_1, it follows the direction of Pipe_Segment_1 and continues moving along this pipeline. When it reaches the intersect of two pipelines, here Node_2, it will communicate with the Pipe_Segment_2 and change its moving direction to the direction of the pipeline until it reaches the next intersection/new node (node_3). At each node, the WW agent gets not only the moving direction of the pipeline but also other pipe attributes to calculate its moving speed inside the pipe following the CalculateSpeed submodel. At each time, the agent will move forward along the designated direction a specific distance. If the moving speed of the agent is smaller than the distance from its location to the next node, it will move forward a distance of its speed, otherwise it will first move to the node and then continue moving forward along the new pipeline a distance calculated by equation 3.14, where the distance_at_segment_2 means the distance that the agent move in the new pipeline, while the distance_left_segment_1 the distance from its current location to the new node. The unit of all speeds in the formula is km/h.

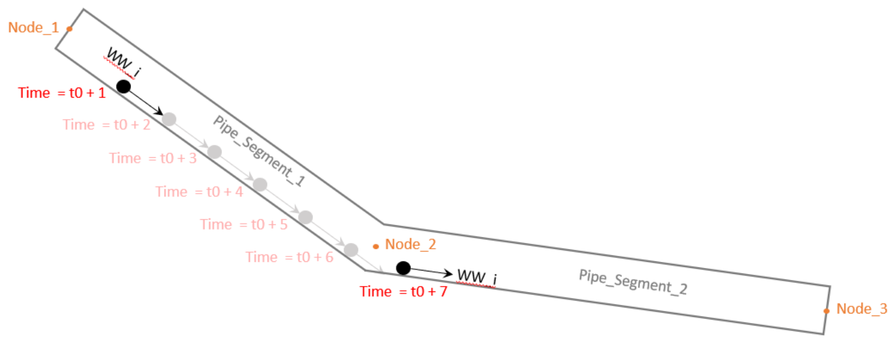


Figure 3.14: the movement of a WW agent

$$distance\_at\_segment\_2 = \left(1 - \frac{distance\_left\_at\_segment\_1}{speed\_at\_segment\_1}\right) * speed\_at\_segment\_2 \qquad (3.14)$$

4 IMPLEMENTATION AND MODEL ANALYSIS

The conceptual model constructed in the last chapter is implemented in the study area - Huehuetla, Mexico, to simulate the real-time wastewater quantity and quality in the city. This chapter starts with a brief introduction of the study area, mainly on its geographical and demographic characteristics, followed by the description of the model parameterisation process during which the values of certain parameters are determined, specially for the study case. Then, typical analyses regarding the model's performance are conducted successively, i.e., robustness analysis, validation, and sensitivity analysis.

4.1 STUDY AREA BACKGROUND

The implementation case of the thesis is Huehuetla, a small city in Hidalgo, in central-eastern Mexico. The municipality covers an area of 262.1 km^2, but the area of the urban region is only 0.4 km² (measured on Google Earth). The study area is covered by only one treatment plant and serves for 726 families and 2815 habitants, and around 300 industrial, commercial, and institutional points, as shown in Figure 4.1, The digital environment of the study area includes the geographical information and attributes of local sewer pipelines and the wastewater treatment plant.

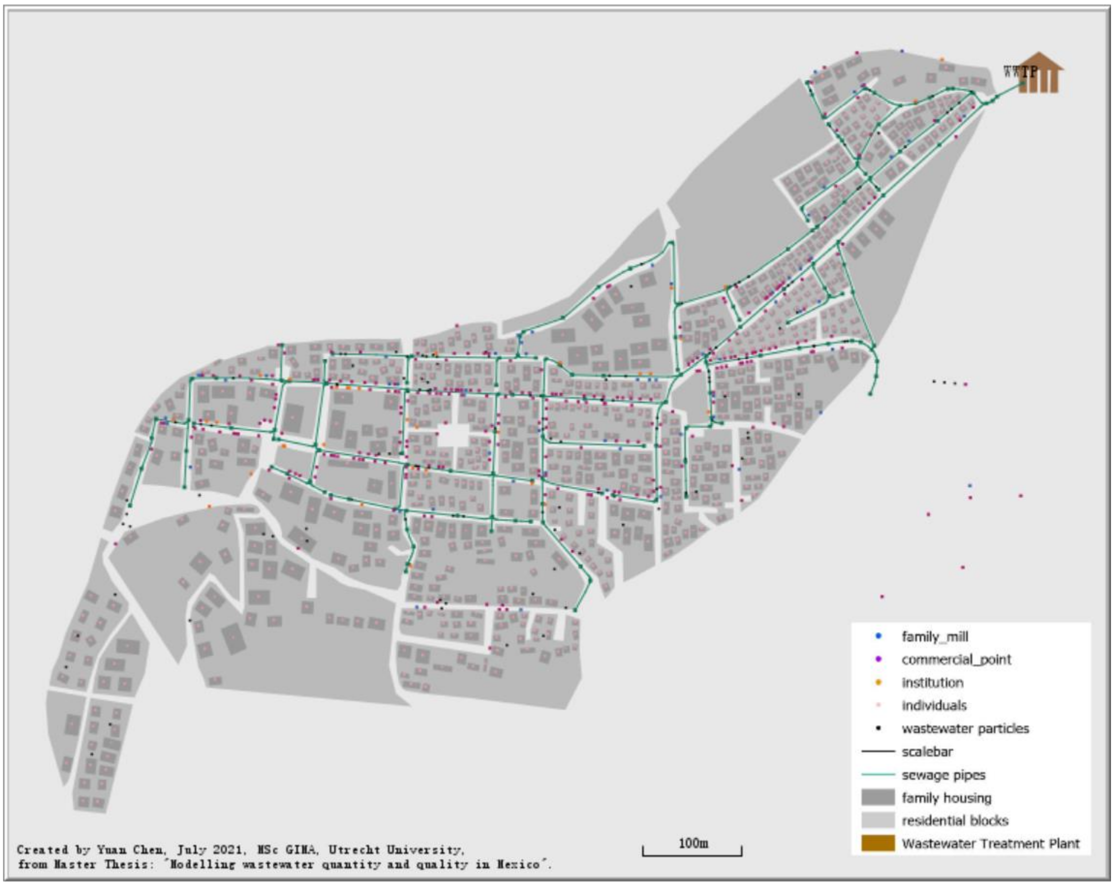


Figure 4.1. an overview of the study area environment

4.2 MODEL PARAMETERISATION

The value of dozens of parameters in the model can be adjusted by the user to match its current study case, as these parameter values embodied the local culture and societal living characteristics, varying from one region to another. Such parameters can be divided into parameters regarding individuals and different types of collectives. Thus, the parameterisation process is conducted for these types of parameters one by one.

4.2.1 INDIVIDUAL

The local unemployment rate of Mexico is 10%, thus 10% of Adult agents generated in each simulation run are randomly selected to be assigned with the *Employment* value of 0. On the other hand, values of parameters representing individual behaviour are determined based on either technical specifications of the most ordinary domestic devices in the market or the generally accepted statistics from human physiology and praxeology as well as social norms and local culture of the study area. The meaning of all these parameters and their values are listed in Table 4.1.

Table 4.1: parameters regarding individual behaviour (source: Water use, 2021)

ITEM	DESCRIPTION	UNIT	VALUE
prob_bath	the average wastewater production of a child taking a bath once, which is only half of the production of an adult/teenager	litre	40
prob_washbasin	the average wastewater production of an individual using the washbasin once	litre	2.0
prob_toilet	the average wastewater production of an individual using the toilet once	litre	5.5
prob_shower	the average wastewater production of an individual taking a shower once	litre	45
washbasin	the average daily frequency of an adult using the washbasin, except the ones after flushing the toilet	times/day	6.0
toilet	the average daily frequency of an adult using the toilet, except the ones after waking up in the morning and before going to bed at night	times/day	4.0
bath4child	the average daily frequency of a child taking a bath	times/day	0.75
bath4teenager	the average weekly frequency of a teenager taking a bath on weekends	times/week	0.02
bath4adult	the average weekly frequency of an adult taking a bath on weekends	times/week	0.04
shower_morning	the average daily frequency of an adult in employment taking a shower in the morning	times/day	0.65
shower_evening	the average daily frequency of an adult in employment taking a shower in the evening	times/day	0.65

According to the general technical specifications in the local market (Technical specifications, 2021), the water consumption of using certain water-demanding devices once depends on their design parameters, such as toilet, shower, and bathtub. A dual flush cistern uses 3 litres for a half flush and 6 litres for a full flush, while a single flush cistern uses 9 to 11 litres per flush. Considering that most local families installed the dual flush, 5.5 litre/flush is adopted as the value of the average wastewater production of using the toilet once. In terms of showering, a water-efficient showerhead uses approximately 9 litres per minute, but this figure can reach 19 litres for an older style showerhead. It is more likely that the new-style showerheads, instead of the old ones, are installed in local families, thus the average wastewater production of an individual taking a shower is set as 45 litres, under the presumption that the average duration of a daily shower is about 5 minutes. As for the activity of using the bathtub, a bathtub uses between 50 to 150 litres of water per fill, depending on the water level. The thesis adopted 80 litres as the average volume of an adult/a teenager taking a bath, while this value decreases to a half for a child taking a bath.

In addition, the washbasin is used for daily activities, including washing hands, cleaning faces, brushing teeth, etc, and around 18 litres per person per day is required for these activities (Technical specifications, 2021). Considering the daily frequency of using the washbasin (explained later), a reasonable value of 2 litres is set as the average wastewater production of using the washbasin once. In experiments, the total water consumption of cleaning faces and brushing teeth (e.g., in the morning/evening) is simply assumed to be two times of the average value of using the washbasin once, and the washbasin is required to be used every time after flushing the toilet.

On the other hand, statistics from human praxeology apply to determining the values of use frequencies of certain devices. For most people, the common times of using the toilet per day is between 6 - 7 in a 24-hour period, but 4 - 10 times a day can also be normal if that person is healthy and happy with the number of times they visit the toilet (Report, 2021). Except the one in the morning after waking up and the one in the evening before going to bed, there are still 4 - 5 times of using the toilet during the daytime, so this value is set as 4. The same report (Report, 2021) also indicates that the use frequency of washbasin is normally 6 - 8 times per day, so the value of the according parameter is set to be 6 in simulation. In general, the frequency of parents bathing their children is more than once two days, thus the bath frequency for children is set as 0.65 times per day but the value itself can vary from 0 to 1. Contrarily, teenagers and adults rarely take bathes, and even they do, they only take on weekends with a quite low probability. The frequencies of an adult in employment taking a shower in the morning and in the evening are determined based on the assumption that working adults have strict requirements for cleanness.

4.2.2 HOUSEHOLD COLLECTIVE

Table 4.2: parameters regarding household collectives' behaviour (source: Water use, 2021)

ITEM	DESCRIPTION	UNIT	VALUE
prob_kitchen	the average wastewater production of an individual when the household collective use the kitchen sink	litre/person	9.0
prob_washing	the average wastewater production of a household collective using the washing machine once	litre/time	305
out_lunch	the average probability of a household collective eating outside for lunch on weekdays	-	0.04
out_dinner	the average probability of a household collective eating outside for dinner on weekdays	-	0.07

The parameters used to depict the behavioural characteristics of household collectives are explained in Table 4.2, including their values set in the model. These values are also derived from technical specifications of domestic devices and people's living habits. At first, the water consumption of using the kitchen sink includes activities of cooking and washing dishes, which, to a large extent, depends on the number of family members. Generally, it takes around 15 to 18 litres of water to fill a kitchen sink. It is believed that this amount is mainly designed for families with 2 - 3 members that is the most common family type in society, so the average wastewater production of using the kitchen sink once is initialised to be 9 litres per person.

Besides, the technical parameters of various types of washing machines in the market shows that a top loader uses 120-150 litres on a normal cycle, while a twin tub uses approximately 70 litres of water on a normal cycle. However, the most prevalent mode of the washing machine in the study area is Samsung WA19J6750LV which consumes 332 litres per full wash cycle. Thus, it is reasonable to adopt 305 litres per wash cycle in the model as the average value of the wastewater production for using the washing machine once, ignoring the impact of the load of dirty clothes on the exact amount.

Other factors impacting the wastewater production in a household are the probabilities of the family eating at home. No survey data about how often local families go out for a meal is available, thus the values of the average frequencies of a household going out for lunch and dinner are set based on the assumption that local families rarely eat out but prefer home-cooked meals. That is why the two related parameter values are fairly low. In addition, the average frequencies of a local family eating out (both for lunch and dinner) on weekends are two times than that on weekdays.

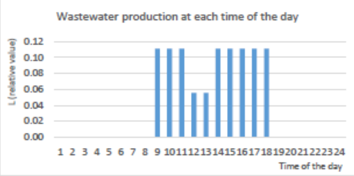
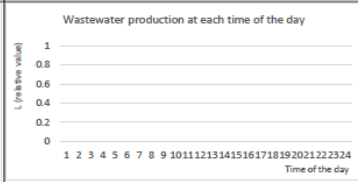
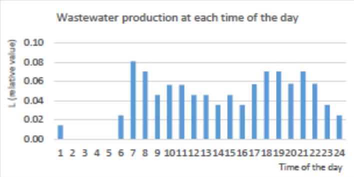
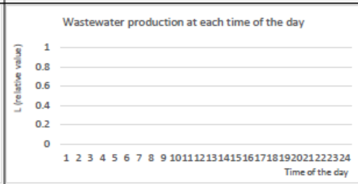
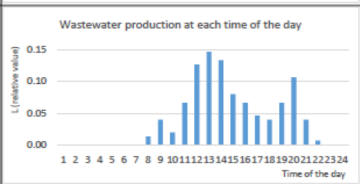
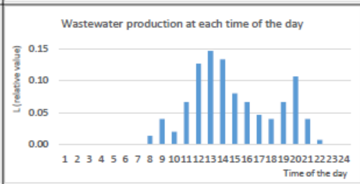
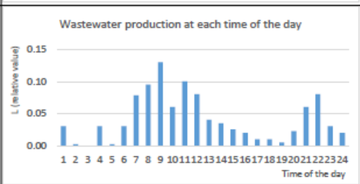
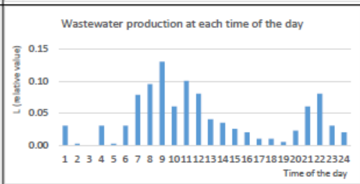
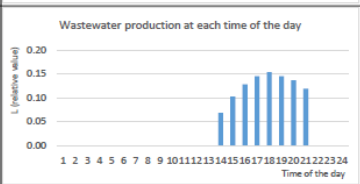
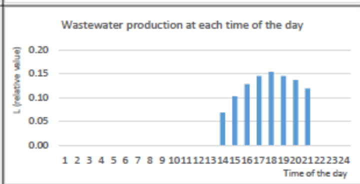
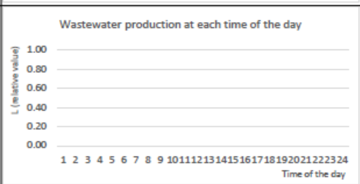
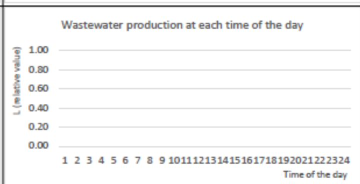
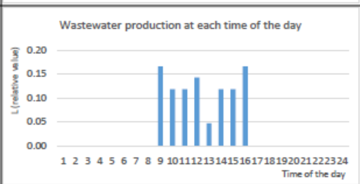
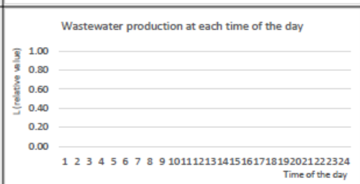
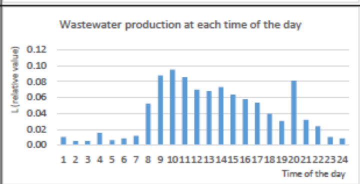
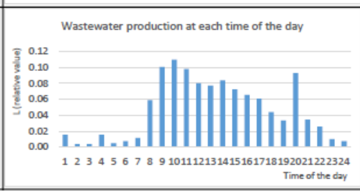
4.2.3 OTHER TYPES OF COLLECTIVES

Values of parameters regarding FamilyMill, CommercialPlace and InstitutionalPlace collectives' behaviour are all derived from literature, as explained in Chapter 2. Then, for a certain collective, its daily wastewater production can be worked out with its *Scale* information. However, the determination of its hourly wastewater production still needs the information of its daily wastewater production pattern (both on weekdays and on weekends). To explain the method of transforming the daily wastewater production of a collective into its hourly values, a FamilyMill collective is taken as an example.

The daily wastewater production of the collective depends on its *Scale* attribute value that indicates how much production is manufactured in the mill every day, and the wastewater quantity for making per unit production. Their relationship is shown in Equation 4.1. Figure 4.2 is the combination result of consulting literature, searching the popular times of a typical instance of the same collective type on Google Maps and making assumptions, showing the daily wastewater production patterns of different subtypes of all these collectives. Based on the daily pattern of the example collective that can be found in Figure 4.2, the wastewater production of the specific FamilyMill collective at each hour can be calculated by equation 4.2. In this way, the hourly wastewater production of each collective can be figured out.

$$\text{Daily\_WW\_production} = \textit{Scale} * \text{WW\_production\_per\_unit} \tag{4.1}$$

$$\text{Hourly\_WW\_production} = \text{Daily\_WW\_production} * \text{proportion\_at\_the\_hour} \tag{4.2}$$

		weekdays	weekends	reference and assumption
FamilyMill	-			1. the ww production in family mills are consistant during the day, except the hours for lunch. 2. workers in family mills are free to choose the time (12:00 or 13:00) to have lunch. 3. family mills do not open at weekends.
Commercial Point	Bakery			1. Shen et al. (2017) shows the common hot water use in bakeries that is regarded to imply the ww production pattern of bakeries. 2. bakeries do not open at weekends.
	Restaurant			1. Fuentes et al. (2018) indicates the typical hourly hot water consumption in restaurants that is approximate to the ww production pattern of restaurants. 2. pattern of weekends is supposed to be the same as that of weekdays
	Hotel			1. Massaguer et al. (2014) depicts the hot water consumption pattern in hotels that is used to reflect on the hotel ww production pattern. 2. pattern on weekends is the same as that on weekdays.
	Bar			1. few literature studied the water-related patterns in bars. Thus, considering that the bar ww production is directly relataed to the number of customers, the ww production pattern is designed similar to the typical popular times of Mexican bars searched on google maps. 2. pattern at weekends is the same as that on weekdays.
	Other			1. the economic activities in other commercial places do not generate wastewater in their processes per se, e.g. retail and wholesale.
	School			1. Garzón-Zúñiga & Buelna, (2011) found that Mexican students only study 6 h/d at school that is assumed to be between 9 - 12 am and 2 - 5 pm. 2. students and working staff use the toilet more often before starting classes and before leaving school. 3. a slight rise at noon is due to lunch, followed by a drop due to the noon rest. 4. schools do not open at weekends.
	Hospital			1. Verlicchi et al. (2013) observed the effluent flow rate (%) of a (French) hospital. 2. Cohen et al. (2016) showed the comparison between the patterns of arrival rates of patients to hospitals on weekdays and weekends, which implies the comparison between hopital ww production patterns at weekends and weekdays.

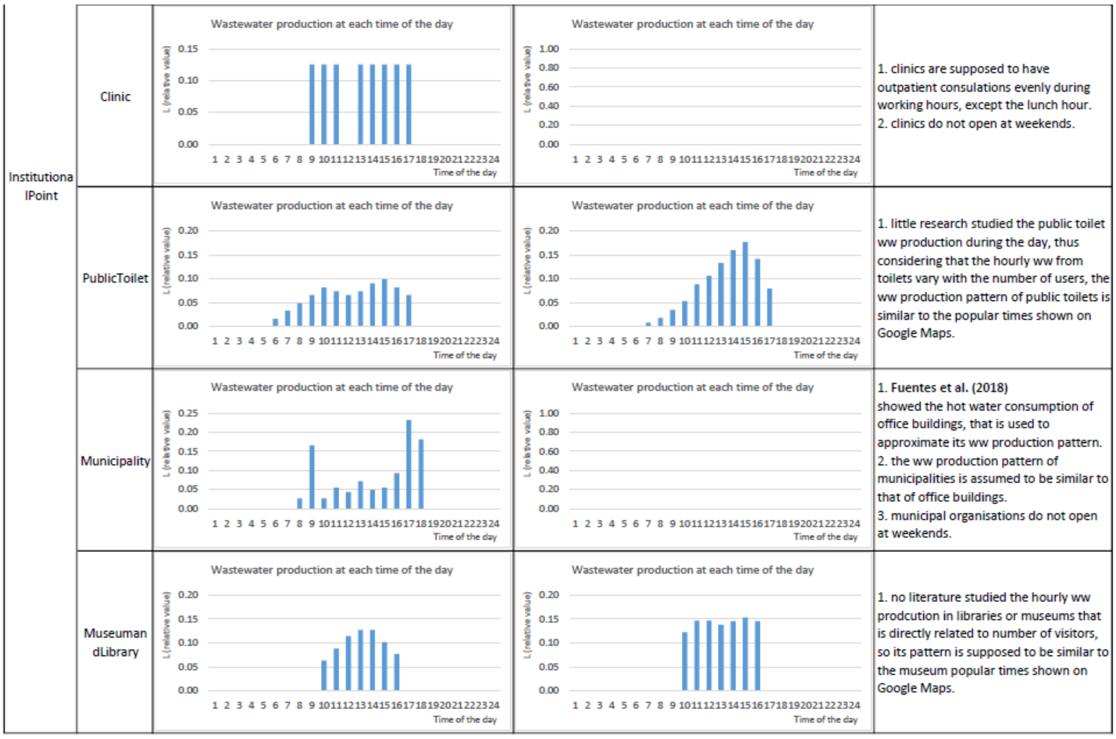


Figure 4.2: daily wastewater production patterns of different types of collectives

4.3 ROBUSTNESS ANALYSIS

Due to the stochasticity designed in the model, it is necessary to carry out the robustness analysis to test the model's stability. For this purpose, two approaches are employed in the thesis. The first one is the plots that depict the accumulative average of certain state variables over an increasing number of simulation runs. Eight variables are observed here: 1) hourly total wastewater inflow to the WWTP; 2) hourly household wastewater inflow to the WWTP; 3) hourly wastewater (produced at family mills) inflow to the WWTP; 4) hourly wastewater (produced in commercial buildings) inflow to the WWTP; 5) hourly wastewater (produced in institutions) inflow to the WWTP; 6) hourly TSS concentration of the wastewater inflow to the WWTP; 7) hourly BOD5 concentration of the wastewater inflow to the WWTP; and 8) hourly COD concentration of the wastewater inflow to the WWTP.

The accumulative averages of all these variables over simulation runs are separately plotted in subfigures of Figure 4.3. It is obvious to conclude from these figures that all indicators tend to stabilise after around 20 simulation runs, and the hourly household wastewater inflow to the WWTP is the first one to reach the stable level that goes to flat after only about 10 times. On the contrast, the curve of the hourly wastewater (from family mills) inflow to the WWTP is always slightly rough but reaching a relatively stabilised status after around 31 runs. The reason of such divergence might be that the people's daily water-use activities in household are relatively regular and stable, while the daily wastewater production of a family mill highly relates to the mill's production of the day that fluctuates somewhat in different days. Curves of the variables indicating the wastewater quality (TSS/BOD5/COD concentration of the wastewater inflow to the WWTP) all reach a plateau after about 25 runs on the whole, although with very minor fluctuations at the late stage.

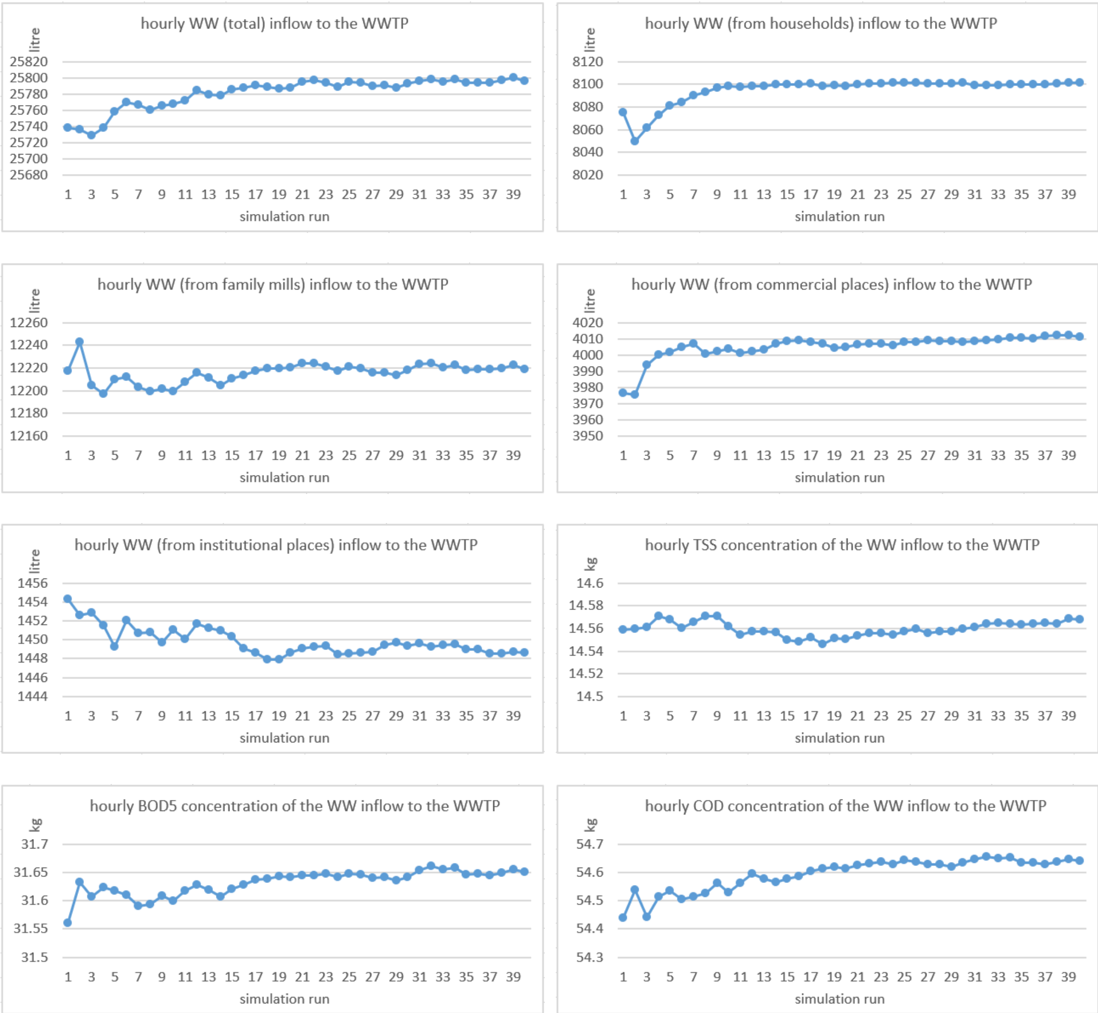


Figure 4.3: accumulative averages of eight state variables over simulation runs

The second approach of testing the robustness of the model is to calculate the coefficient of variance of the same state variables, namely the ratio between the standard deviation of a sample and the mean of that sample, resulting in the formula: $CV = \sigma/\mu$. The CV values of the variables abovementioned are shown in Table 4.3, from which the same conclusion as that of the first approach could be drawn.

Table 4.3: coefficient of variance (CV) of the state variables

Run Times	TOTAL	HOUSEHOLD	FAMILYMILL	COMMERCE	INSTITUTION	TSS	BOD5	COD
10	0.000615	0.001956	0.001115	0.002866	0.001046	0.000348	0.000640	0.000734
20	0.000768	0.001798	0.000856	0.002321	0.001171	0.000527	0.000643	0.000946
30	0.000767	0.001601	0.000773	0.002040	0.001090	0.000437	0.000664	0.001043
40	0.000743	0.001428	0.000716	0.001939	0.001000	0.000435	0.000688	0.001040

4.4 VALIDATION

The validation step in the thesis aims to test the effectiveness of the model from the aggregative level. It is realised by comparing the model results with the information provided by the design blueprint of local pipelines and the findings of other literature. This analysis is carried out from two aspects: figures related to household wastewater production and figures related to the wastewater generation of all types of collectives.

4.4.1 HOUSEHOLD WASTEWATER PRODUCTION

1) total volume

In the model, the household wastewater production and pattern on weekdays differs considerably from that on weekends. The time series of hourly wastewater production from all households in the study area during a week (blue line) is shown in Figure 4.4, together with its average value of the week (red line). The daily wastewater production averages out at about 336.969 m^3 in the study area for 2815 habitants, and thus 119.705 litres per day per habitant that highly coincides with the figure 120 litre/day/habitant marked in the blueprint of the 'Rehabilitation of the Pipelines' of the study area.

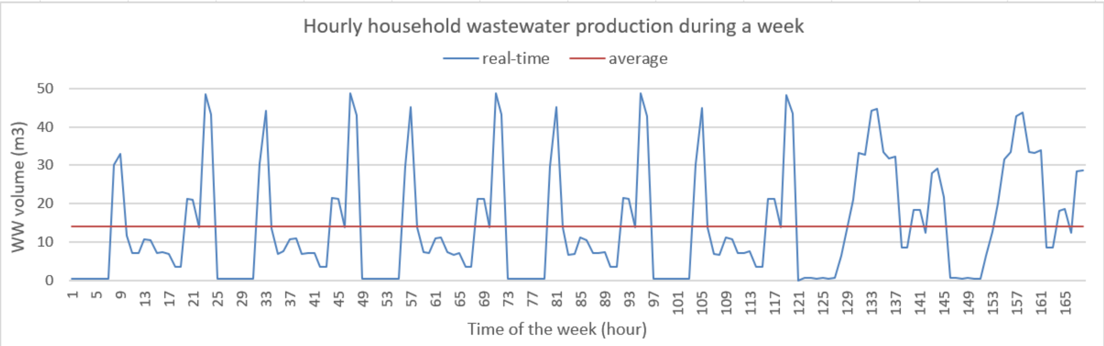


Figure 4.4: hourly production of household wastewater during a week

2) composition by domestic water-demanding device

The proportions of the volume of wastewater produced via different domestic water-use devices (i.e., bathtub, washbasin, toilet, shower, kitchen sink and washing machine) accounting for the total household wastewater production are utterly disparate. These proportions also vary with if it is on weekdays or weekends. Thus, to get an overall picture of how much each type of water-use practice contributes to the total production, weekly productions of these activities, instead of their daily amounts, are employed here to calculate these proportions.

The model result is shown in Figure 4.5 (left), in comparison with the findings of AybuĞa & IŞildar (2017) on the right. It is obvious that the classification systems for wastewater sources in the two pie charts are not exactly the same. Thus, for the sake of simplicity, the options of 'Dishes Washer', 'Leakages' and 'Others' in the right chart are all considered as 'kitchen sink' on the left. In this way, the structures of the two pie charts are almost the same, showing the same trend: the wastewater production from showering accounts the most (30%), followed by using the washing machine (21%) and flushing the toilet (20%); the last three places are respectively for the washbasin (on the left) or faucets (on the right) (16%), the kitchen sink (10%), and the bathtub (3%).

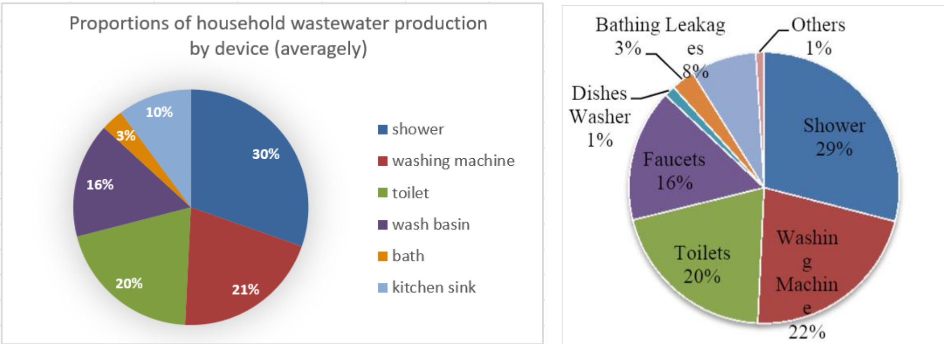


Figure 4.5: proportions of different water-use activity productions

3. Daily Pattern

As shown in the left subfigure of Figure 4.6, the daily pattern of the hourly household wastewater production differs markedly on weekdays (blue line) and weekends (green line). To validate this model output with precursors' research results, the former adopts the average daily pattern during a week that is also plotted in Figure 4.6 left (red line), while the latter takes the research result of Gato-Trinidad et al. (2011) as a poster child that is shown in Figure 4.6 right. Among all the curves in the right subfigure, the one of dark red solid line draws the time series of the typical hourly household wastewater production in a day and thus is taken into comparison.

There is an obvious temporal delay of one hour between the two curves, i.e., the red one on the left and the dark red one on the right. The reason may be that, for instance, the production at 9:00 am in the thesis represents the amount of wastewater between 8:00 am - 9:00 am, while the value of the same time in the research of Gato-Trinidad et al. (2011) means the wastewater production during 9:00 am - 10:00 am. In other words, due to the temporal resolution, the value at 9:00 am in the thesis is the counterpart of the value at 8:00 am in Gato-Trinidad's research.

If this temporal delay is corrected manually, the two curves in comparison will be quite similar in terms of the trend and extent of wastewater quantity changing over hours. Besides, certain characteristics regarding household wastewater production can be found easily in both curves. In general, it appears a decreasing trend from 9:00 am to 6:00 pm, and an increasing trend between 7:00 pm and 12:00 pm, although both trends involve minor fluctuations. Besides, the curve between 1:00 am and 7:00 am is almost flat with the variable value near 0. Most obviously, the two distinct peaks appear at around 9:00 am and 11:00 pm, whilst the only basin lies at around 6:00 - 7:00 pm. Such characteristics basically conform with the typical daily behavioural pattern of people in realism.

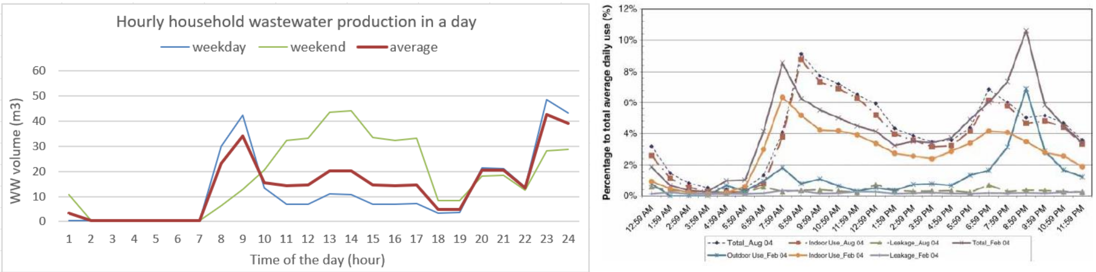


Figure 4.6: average hourly wastewater production at the household in a day

On the other hand, Figure 4.7 represents the daily patterns of average hourly wastewater production via different household devices, with the left subfigure drawing the result of the thesis model and the right one the results of Gato-Trinidad et al.'s research (2011). Clearly, there is a great similarity between the two subfigures, which is reflected by the evident characteristics shared by both.

The daily trend of using the toilet has two peaks, with one peak at around 9:00 am and the other between 10:00 - 11:00 pm, and even the variation of the two according curves are quite alike. 'Other Indoor Uses' in the right subfigure is regarded as the counterpart of the washbasin use in the left one. In this way, both curves reach their two peaks at 9:00 am and 8:00 pm, respectively. The pattern of the total use of the shower and the bathtub in the left figure is somewhat consistent with the curve of 'Showers & Baths, Spas' on the right, with their first use peak both at around 9:00 am but their second peak hour different. This might be partly because of the different living habits of local people. In terms of the pattern of using the washing machine, its curve from Gato-Trinidad et al.'s research has ups and downs with a tail at night, while the model result of the thesis shows a stable trend and only during the daytime. Such divergence may have to do with the assumption made in the thesis to simplify the regularity of people using the washing machine in the study area.

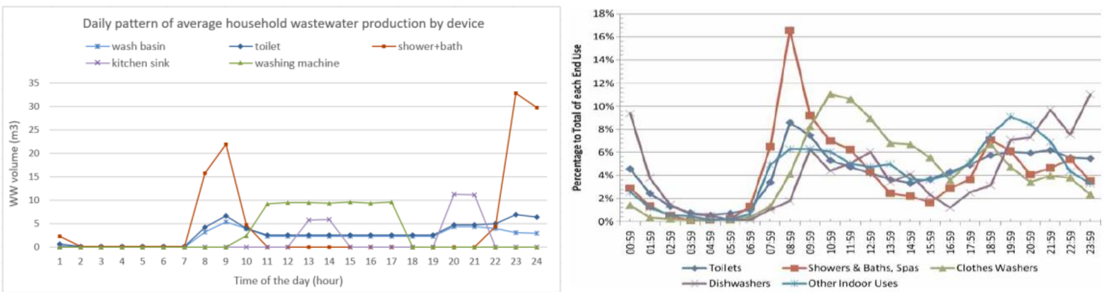


Figure 4.7: average hourly wastewater production from different domestic devices

4.4.2 WW PRODUCTION OF DIFFERENT COLLECTIVES

Another group of indicators used to validate the model relates to the wastewater production of different types of collectives, but because of the lack of actual monitoring data, only one indicator of this type is under consideration which is the proportion of the wastewater quantity of each collective type accounting for the total production in the study area. Certainly, these values vary greatly with if it is on weekdays or weekends, just like Figure 4.8 that plots the weekly time series of hourly wastewater production of different collective types. The daily volume of a weekday differs markedly from that of a weekend for household collectives and family mill collectives, but such a difference is indiscernible for other two types. Accordingly, the average proportions of all types of collectives constitute the pie chart in Figure 4.9. It clearly indicates that households (42%) dominate the wastewater production of the entire study area, while the rate of the amount from family mill collectives is in the second place, accounting for 41%.

On the other hand, based on the report of APEC, for the total available water in Mexico, 77% is used by the agricultural sector, 9% by the industrial and services use, and 14% for the consumption of the population (ESA report, 2007). That is to say, except for agricultural water use, industrial use accounts for around 40% of the total urban water use, and others are used for human's daily uses, i.e., household use, commercial use, and institutional use. It is acceptable to use such values to approximate the situation of wastewater production, thus this report figure is consistent with the model result.

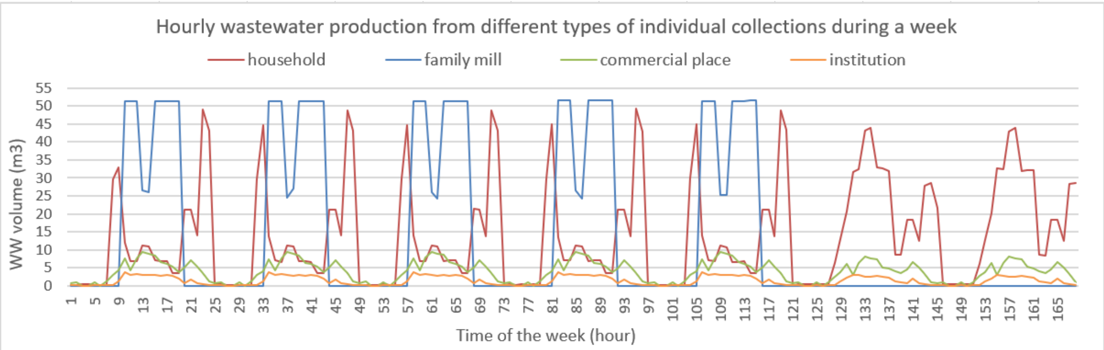


Figure 4.8: comparison of WW production by building during a week

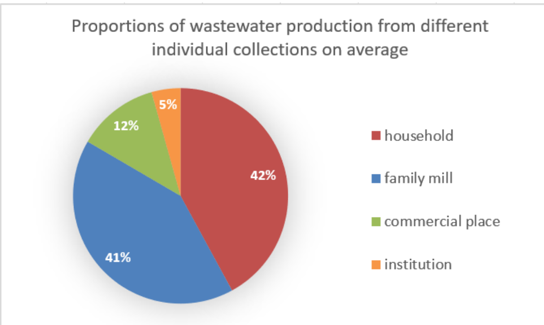


Figure 4.9: average proportions of WW volume by building on a typical day

4.5 SENSITIVITY ANALYSIS

Sensitivity analysis is used to test how sensitive the model result is to its inputs, which can be measured by the extent to which the model result is affected by the change in initial values of its input variables (individual or combined). If the model is highly sensitive to a variable, then even a minor fluctuation in its value can lead to a substantial variation in the model output, and vice versa. Table 4.4 lists the three aspects from which the sensitivity analysis of the thesis is conducted.

Table 4.4 sensitivity analysis schema

Parameter	Question	How to Identify	What to Measure
population	if the distribution of the population in the study area impacts the result?	change the population distribution in different simulation runs	weekly time series of the hourly HWW production
consciousness	if the spatial distance in defining neighbourhood impacts the public consciousness level?	change the distance of neighbourhood in different simulation runs	70-day time series of the daily public consciousness level
	if the communication frequency with neighbours impacts the public consciousness level?	change the communication frequency (daily, weekly, monthly) in different simulation runs	3-month time series of the daily public consciousness level
	if the change in public water-saving consciousness leads to wastewater reduction?	change the consciousness value of all individuals simultaneously in different simulation runs	daily time series of the average hourly HWW production
flow velocity	if the flow velocity has an impact on the pattern of the WW inflow to the WWTP?	change the velocity of WW agents inside the network in different simulation runs	weekly time series of the hourly WW inflow to the WWTP

4.5.1 POPULATION

Population here particularly refers to the age distribution of local habitants in the study area, namely the number of each type of people, i.e., child, teenager, adult and senior. The population in the model is generated via Synthetic Population Generation method based on census data which provides only the numbers of young people (including children and teenagers), adults and seniors. Therefore, there is always a slight difference in the numbers of children and teenagers generated in different simulation runs, and thus the age distribution of the population. The sensitivity analysis on population is carried out to test whether such a nuance in generated populations has a noticeable impact on final outputs of the model. For this purpose, the output adopted here is the hourly household wastewater production.

The weekly time series of the targeted output for different populations generated in five separate groups of simulation runs are plotted in Figure 4.10, with the age distribution of each Type of population explained in Table 4.5. It can be easily found from the figure that these curves almost overlay mutually, with only a minor discrepancy in the values of turning points. That is to say, the minor change in the age distribution of population does not have a great impact on household wastewater production, neither on its trend nor its values.

Moreover, the coefficient of determination (R^2) is introduced to quantify the similarities between these curves in the mathematical way. R^2 quantifies the degree of any linear correlation between $Y_{observe}$ and $Y_{predict}$, and for the goodness-of-fit evaluation, with only one specific linear correlation in consideration: $Y_{observe} = 1 \cdot Y_{predict} + 0$ (Coefficient of determination, 2021). If we consider the time series of one Type of population as the base value ($Y_{observe}$), and that of another Type as the comparative value ($Y_{predict}$), then R^2 can be used to evaluate the closeness between the two curves. In this way, R^2 of the curves of different populations are calculated and their values are listed in Table 4.5 where the population of Type 3 is regarded as the benchmark for each R^2.

With the threshold for R^2 set as 0.8, meaning that when R^2 is higher than 0.8, the two curves in comparison are considered as similar, the figures in Table 4.5 proved that the five time-series of the hourly household wastewater production corresponding to the five different populations are nearly identical. Thus, the same conclusion as the one from the figure can be drawn: the main population-related model result – the household wastewater production, is not sensitive to the age distribution of population generated based on census data.

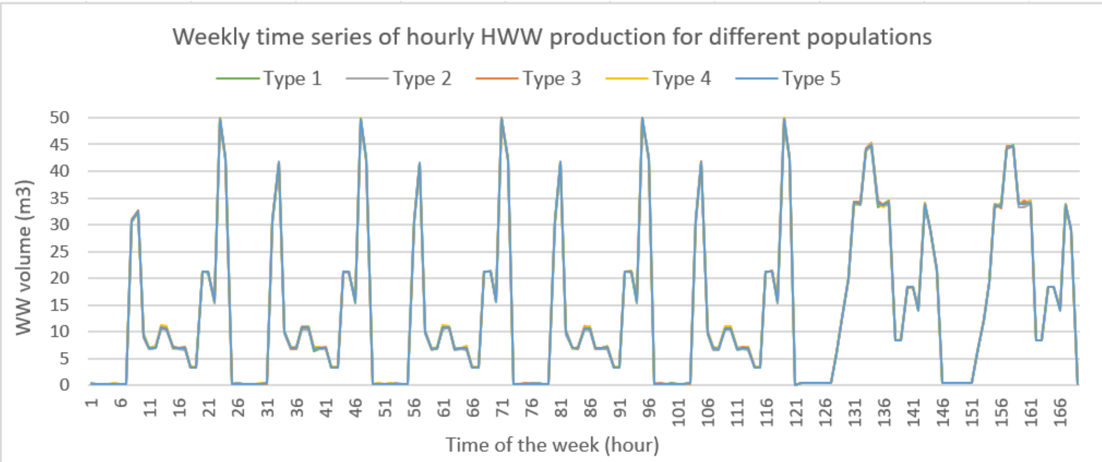


Figure 4.10: hourly household wastewater production for different populations

Table 4.5: coefficient of determination of different populations (Type3 as the benchmark)

Types	Num. of children	Num. of teenagers	Num. of adults	Num. of seniors	R2
Type 1	268	575	1661	311	0.94
Type 2	280	563	1661	311	0.94
Type 3	292	551	1661	311	1
Type 4	301	542	1661	311	0.96
Type 5	310	533	1661	311	0.97

4.5.2 CONSCIOUSNESS

It is clear in the conceptual modelling phase that individual water-saving consciousness matters a lot to household wastewater production. In this part, how sensitive the model is to consciousness-related parameters is studied, including the sensitivity of the global consciousness level to the neighbourhood range and to the frequency of social interaction, as well as the sensitivity of the wastewater reduction to the rise or decline in the public consciousness level.

1) the neighbourhood range

As elaborated in the ChangeCons submodel, the water-saving consciousness value of an individual is impacted by its neighbours, that is to say, this kind of influence is only limited within a certain distance. The neighbourhood range of a point defines the largest distance the points within which are seen as the neighbours of the target point. This parameter value is homogeneous for all individual agents in the model. The sensitivity analysis here is to test the sensitivity of the public water-saving consciousness level to the neighbourhood range.

Figure 4.11 shows the time series of the daily public water-saving consciousness in 10 weeks where the neighbourhood range is respectively set as 10, 15, 20, 30, 40, 50, 100, and 150 in the virtual environment, representing the distance of 15.84m, 23.76m, 31.68m, 47.51m, 63.35m, 79.19m and 158.38m in realism. The interaction frequencies in these experiments are all set to be weekly, so that all curves are serrated with regular (weekly) fluctuations. It can be found from the figure that the public consciousness level varies widely from one neighbourhood range to another. The larger the range, the higher the level, but when the range exceeds a certain large value (e.g., 100), the level of public consciousness approximates to a plateau with little rise in its value. Thus, the conclusion can be drawn that the neighbourhood range has a tremendous impact on the public consciousness level. The thesis adopts 30 as the standard neighbourhood range, as its overall trend is more like the change of human's awareness in real life.

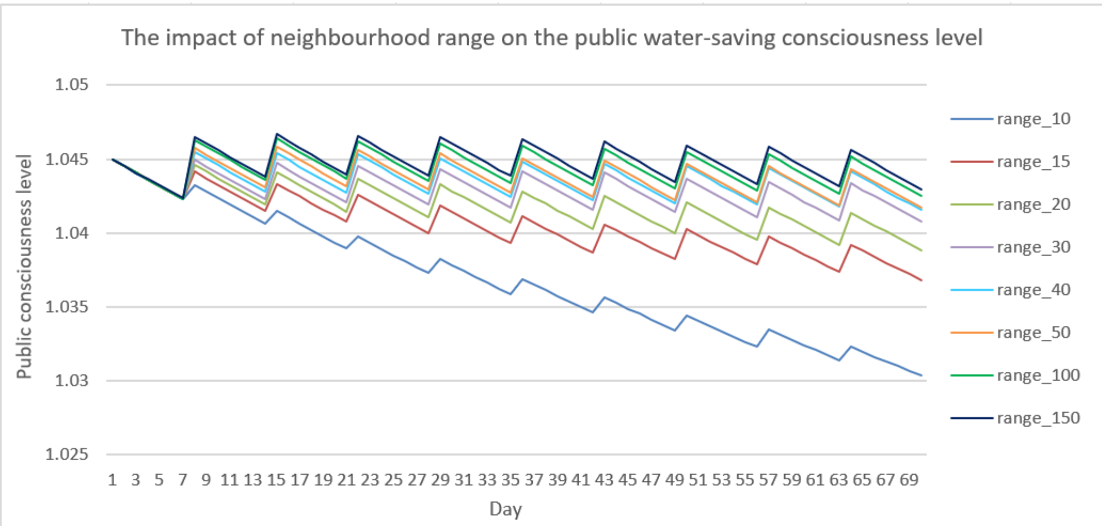


Figure 4.11: time series of the daily public water-saving consciousness level under different neighbourhood ranges

2) interaction frequency (daily vs. weekly vs. monthly)

Similar to the neighbourhood range, the interaction frequency is another factor for quantifying the neighbouring influence on individual water-saving consciousness. This parameter value also applies identically to all individual agents, indicating how often an individual communicates with its neighbours in terms of the awareness of conserving water. The sensitivity analysis on the interaction frequency is to test how sensitive the public water-saving consciousness level is to the frequency of the social interaction among individuals.

For this purpose, three frequencies are experimented separately, i.e., daily, weekly, and monthly (four-weekly). Their time series of the daily public water-saving consciousness value spanning 3 months (12 weeks) are plotted in Figure 4.12 with the neighbouring range all set as 30. It is obvious that the interaction frequency greatly influences the trend of public awareness over time. When individuals interact with each other daily, the overall level of public awareness remains at a very high value, even higher than its initial value, while in other two cases, this value declines slightly over time with the one of monthly frequency decreasing the most. Therefore, we can conclude confidently that the water-saving consciousness level is sensitive to the frequency of individual social interaction. The thesis adopts the weekly frequency as the basic case, as it is much closer to the actual situation of social interaction.

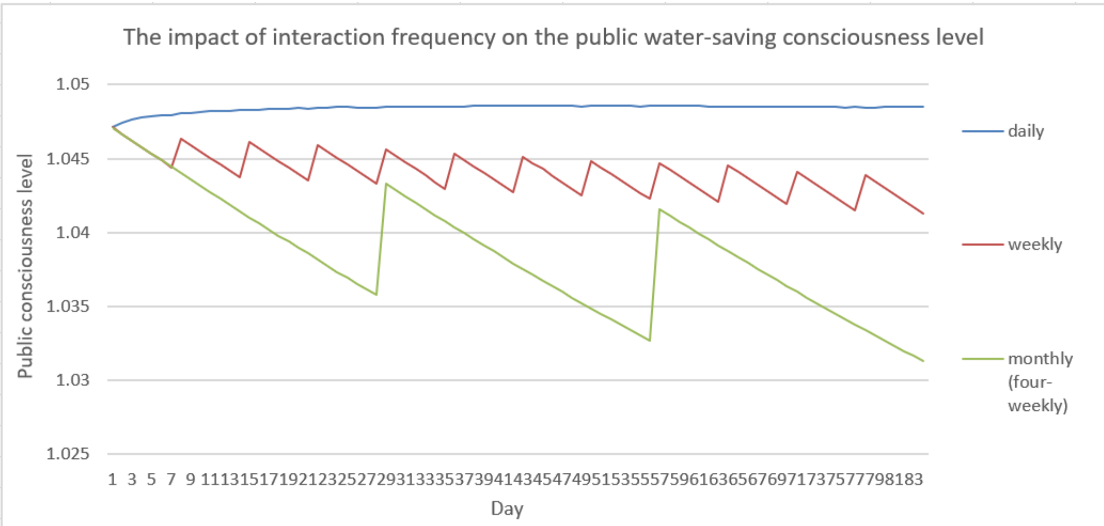


Figure 4.12: time series of the daily public water-saving consciousness level under different interaction frequencies

3) public water-saving consciousness level and wastewater reduction

This subsection deals with the quantitative relationship between global water-saving consciousness and wastewater reduction, that is to say, the sensitivity of the actual wastewater reduction to the public water-saving consciousness level. This analysis compares the daily time series of the average hourly household wastewater production under different public consciousness levels which are plotted in Figure 4.13, and the average values of these curves are calculated and shown in Figure 4.14 for an intuitive expression. Different levels stand for different values of the average individual water-saving consciousness. Level_0 is the base level of public awareness where the value of the average individual consciousness is 1.05, while for other levels, each time the level goes up or down by 1, the average individual consciousness value rises or declines by 0.1. For instance, level_-1 means the average individual value that is decreased by 0.1 based on level_0, and level_-2 by 0.2, and so on, whereas level_+1 refers to the variable value that is 0.1 more than the value of level_0, and level_+2 is 0.2 more, and so on.

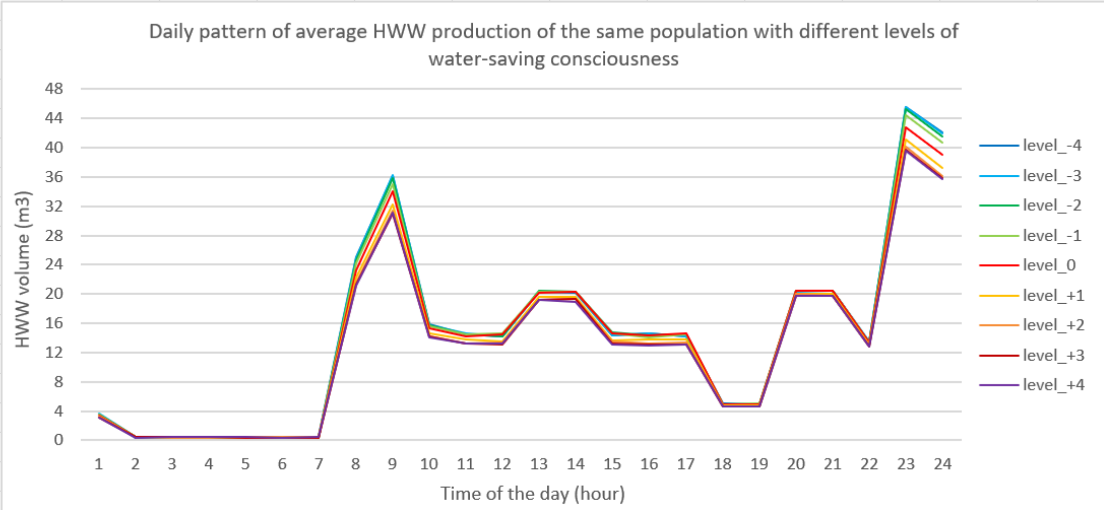


Figure 4.13: reduction in wastewater production due to the rise in consciousness

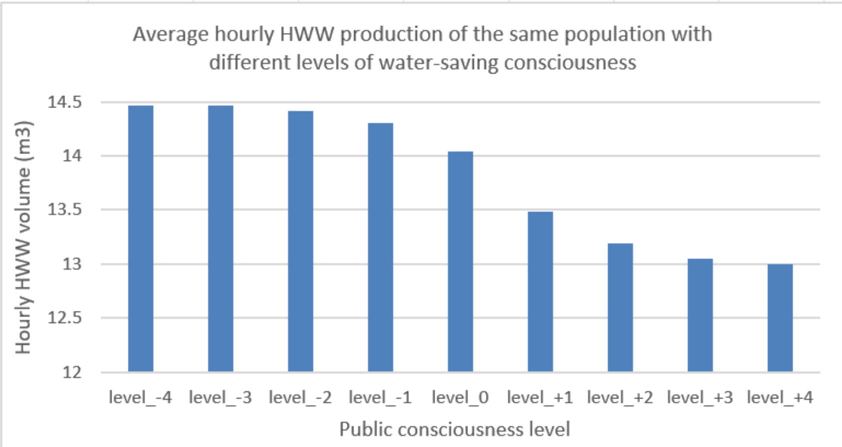


Figure 4.14: hourly household wastewater production for different public awareness levels

Both Figure 4.13 and 4.14 show the same conclusion: household wastewater production is in an inverse sigmoid relationship with public water-saving consciousness. That is to say, wastewater production decreases with the increase of public awareness and vice versa, and the change in public awareness whose level is closer to the base level leads to more variation in wastewater production than those whose levels are away from the base level. Besides, the daily reduction in HWW production caused by a unit increase in public awareness level near level_0 is between 6.24 and 13.43 m3 for the whole population, namely 2.22 - 4.77 litre/person/day which conforms with the value of 4.3 - 4.6 litre/person/day in the research of Domene & Saurí (2006). It can also be found that the reduction effect of rising water-saving consciousness is more obvious in peak hours of a day, since both production peaks that are during 8 - 9 and during 22 - 24 decrease considerably, compared to other time slots. Therefore, if the government aims to reduce the daily peak production to a reasonable extent, it will be a good option to boost the public awareness of saving water, e.g., by organising a water-saving campaign.

4.5.3 FLOW VELOCITY

In principle, the flow velocity normally has a considerable impact on the final inflow rate to the WWTP. But how the impact varies with the velocity in practice depends on the actual study case. The sensitivity analysis regarding flow velocity is to test how the time series of the inflow rate to the WWTP changes with flow speed. As shown in Figure 4.15, several subfigures are grouped together, each comparing the time series of the hourly inflow to the WWTP at the base speed and at a comparative speed, except for the first subfigure. The first one compares the total hourly wastewater production across the entire study area with the hourly wastewater quantity reaching the WWTP at the actual flow velocity. The actual speed is calculated according to the Velocity submodel elaborated in chapter 3 and it also works as the base speed in following figures. It is easy to find from the first subfigure that the two time-series are completely identical, meaning that the wastewater produced in the study area can all reach the WWTP within one hour, which is exactly the case in realism.

The following subfigures take the actual speed as the base flow speed and a percentage of it as the comparative speed, and compare the weekly time series of hourly wastewater inflow to the WWTP based on the two speeds. Since all speeds faster than the actual speed will lead to the same result as the first subfigure, the comparative speeds in other subfigures are respectively set as 1/10, 1/100, 1/200,1/300,1/400 and 1/500 of the actual value. In the second one (1/10), there is an obvious time delay between the two curves with the comparative curve smoother, but their change patterns are highly similar. With the speed decreasing gradually from 1/10 to 1/200, the curve of the comparative speed is becoming flatter with minor fluctuations and the effect of time delay is still detectable but not evident. However, this trend starts to change after the speed drops to 1/300 of the real value. As the speed decreases further, the curve of the inflow to the WWTP fluctuates more widely and regularly again, like the curve of the real-life speed, but such fluctuation is smaller, and the time delay is remarkably clear. When the speed falls to 1/400 of the real value or lower, the time series of the inflow rate seems unvarying with the speed because of the high similarity between the last two figures.

Therefore, the conclusion can be drawn from the figures that the flow velocity certainly has a significant impact on the final wastewater inflow rate to the WWTP, and in the study case, when the speed falls to around 1/200 of the real-life value, the time series of the hourly wastewater inflow to the WWTP will be the flattest with little variation in time, compared with the curves of other speeds. Considering from the standpoint of the designer of the WWTP capacity, the flatter the wastewater inflow rate to the WWTP, the better, because the wider the fluctuation, the higher capacity the treatment plant has to be designed with and the higher the cost. In this way, if possible, when designing/updating the pipelines (the flow velocity highly depends on the parameters of pipelines), the flow velocity is better to be controlled around 1/200 of the current velocity.

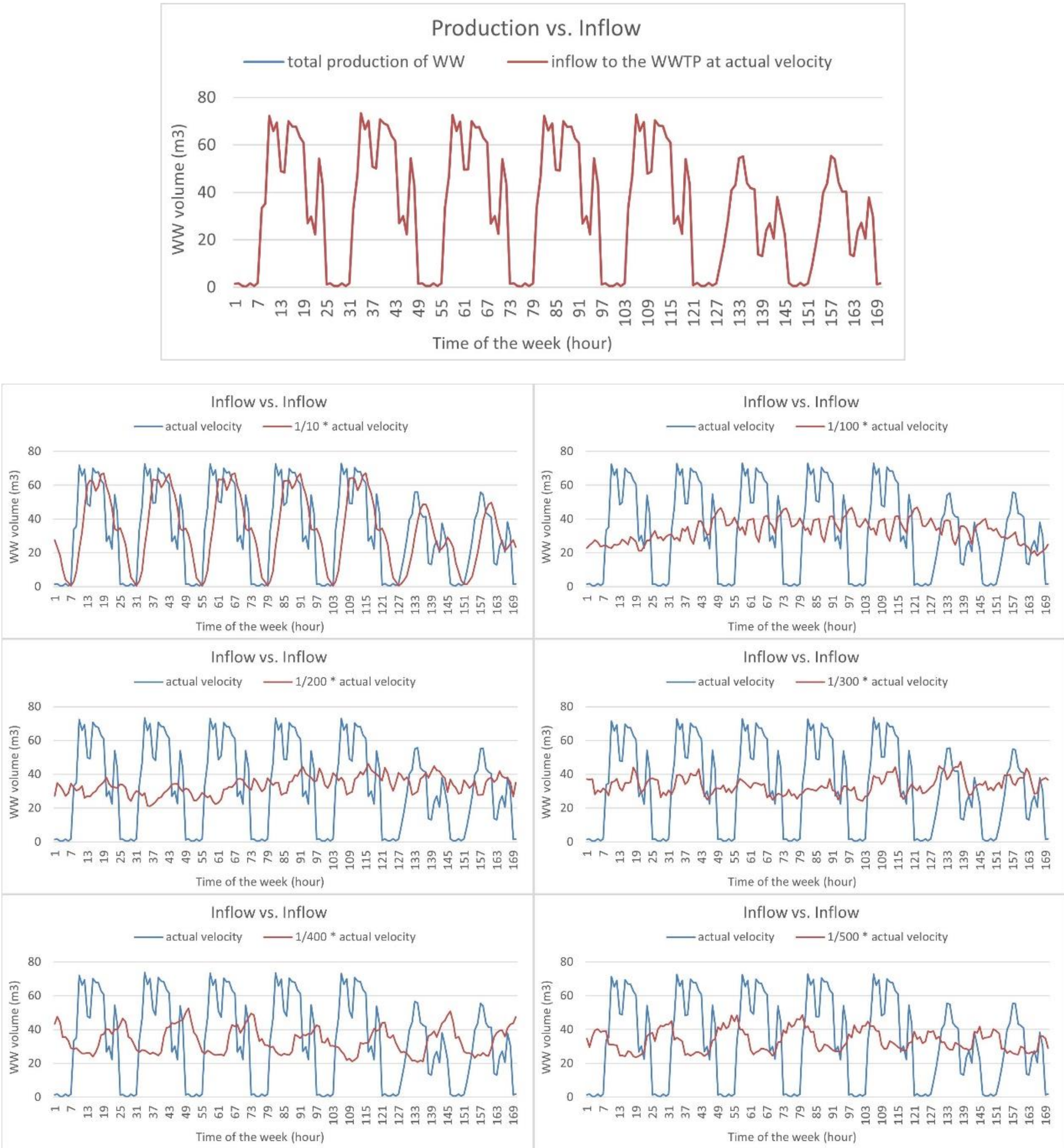


Figure 4.15: hourly wastewater inflow to the WWTP under different flow velocities

5 RESULTS AND ANALYSIS

This chapter shows the simulation results of the model and based on that, analyses the situation of wastewater generation in the study area. Then, scenario experiments are carried out to assess the measures quantitatively that may be taken by the government and to give some insights into future water policies.

5.1 RESULTS

Some interesting findings about the current situation of wastewater quantity and quality of the study area are demonstrated here, including the comparison of wastewater production patterns on weekdays and weekends, as well as the comparison of household wastewater production among diverse families.

5.1.1 WEEKDAY VS. WEEKEND

The model is characterised by the enormous disparity in wastewater production patterns between weekdays and weekends. Such difference can be exhibited in the following three aspects.

1) wastewater quantity from different collective types

Due to the difference in the behavioural patterns of individual agents and collectives on weekdays and weekends, the time series of hourly wastewater quantity from each single collective varies markedly from weekday to weekend. The comparison results are shown in Figure 5.1, with the left subfigure depicting the time series of the hourly wastewater production from different collective types on a weekday, while the right one plotting the same thing during a typical weekend. Accordingly, the proportions of all collective types accounting for the total production on weekdays (left) and weekends (right) are separately calculated and compared in Figure 5.2.

In terms of quantity, both figures clearly demonstrate that family mills produce the most wastewater on weekdays, followed by households, whereas on weekends, households dominate the urban wastewater generation but the volume of wastewater from family mills drops to zero. This is because it is assumed in the model that family mills are closed on weekends. The other two types of collectives only account for a small part in the total wastewater production, no matter on weekdays or weekends. In terms of the production pattern, household wastewater changes a lot, as its peaks on weekdays are between 8 - 10 and between 22 - 24, and that of weekends are the whole daytime, especially at noon. The daily pattern of commercial places does not change noticeably, while that of institutions varies obviously from weekday to weekend but still to a small degree if compared with the variation in the pattern of household wastewater production.

Figure 5.1: time series of hourly WW volume by collective on a weekday and a weekend

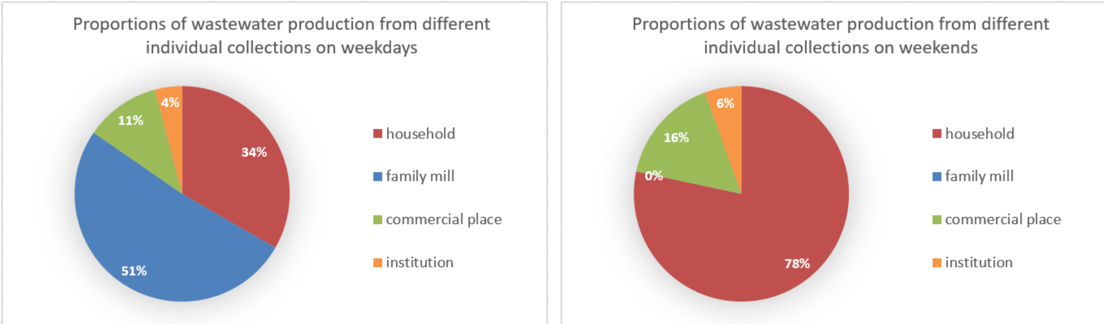


Figure 5.2: proportions of hourly WW volume by collective on a weekday and a weekend

2) wastewater quantity from different water-demanding devices

The difference between weekday and weekend also lies in the wastewater quantity via different domestic water-demanding devices. The daily wastewater production pattern of each device varies considerably depending on if it is on weekdays (left) or weekends (right), as shown in Figure 5.3. Obviously, the curves of the washing machine in the two subfigures differ the most, followed by that of the shower and the kitchen sink. The hourly volume of wastewater from washing machine in the daytime on weekends is much higher than that on weekdays. Such a phenomenon should be highly linked to the assumption of the model that local families are habituated to wash clothes on weekends. The two peaks in the time series of the hourly volume of wastewater via the shower on weekdays are more distinct than that on weekends, especially the one around 9 - 10 am. The reason behind such dissimilarity is probably that adults take a shower more often before going out for work and sometimes before going to bed. The evident rise in the amount of kitchen wastewater at lunchtime on weekdays over weekends is probably because adults are less likely to cook lunch at home on weekdays due to work.

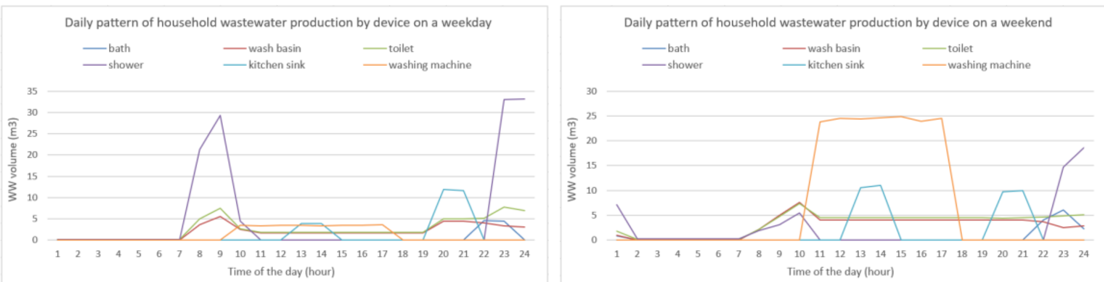


Figure 5.3: time series of hourly HWW production by device on a weekday and a weekend

Accordingly, proportions of the wastewater production via different household devices are calculated for weekdays and weekends, and their distributions are illustrated in the left and right subfigure of Figure 5.4, respectively. Some similar conclusions as above can also be drawn. On weekdays, wastewater mainly comes from showering, followed by the toilet and the washbasin. This highly relates to the reason that many adults have to go out for work on weekdays and thus keep a high-level cleanliness. On the contrary, people are likely to tidy the room and wash clothes on weekends, so that the washing machine contributes the most to the total wastewater production. The second and third places of weekend are showering and kitchen use, respectively, which matches people's habits of cooking more at home and showering less on weekends. By comparing the two subfigures, proportions of wastewater production via the washing machine and the shower differ greatly from weekday to weekend, while that of the kitchen sink, the bath and the washbasin do not change at all, and that of the toilet vary only to a small extent.

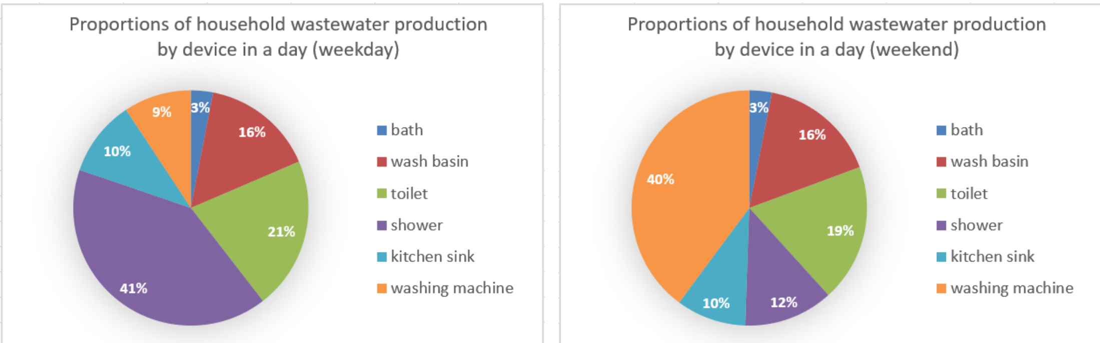


Figure 5.4: proportions of hourly HWW production by device on a weekday and a weekend

3) wastewater quality

A large disparity also exists in the wastewater quality between weekdays and weekends. Wastewater quality means the content of TSS, BOD5 and COD in the mixed wastewater from all collectives, i.e., households, family mills, commercial places, and institutions. Such disparity is partly brought about by the substantial difference in wastewater production patterns between weekdays and weekends. Figure 5.5 represents the content of TSS, BOD5 and COD from each collective type at hourly intervals during an entire week, with each indicator illustrated by one subfigure correspondingly.

All the three subfigures show a common feature. Water pollution is mainly derived from the wastewater of family mills, as it is clearly shown that the amounts of TSS, BOD5 and COD from family mills are much higher than that from households, commercial places, or institutions on weekdays, but on weekends, these values of family mills drop to zero due to their regular close on weekends. Besides, compared to BOD5 and COD, the content of TSS from households or commercial places forms a larger proportion of the total amount. Moreover, the Institution collective type contributes to a rather small degree to the total amounts in terms of all quality indicators.

Therefore, it is reasonable to conclude that wastewater from family mills (namely from (semi-)industrial processes) is the predominant source of water pollution in the study area, such as the slaughtering and dying processes. A recommendation can be further made that the local government can encourage and support local family mills to preliminarily purify their wastewater outflow before inflowing to the treatment plant, such as installing simple, small, and cost-effective technology that is specified for their own manufacturing processes. In this way, it could be of great help in improving the quality, especially in decreasing the contents of BOD5 and COD of the wastewater inflow to the WWTP, thereby mitigating the heavy workload of treatment plants and thus the investment for building/maintaining these treatment machines.

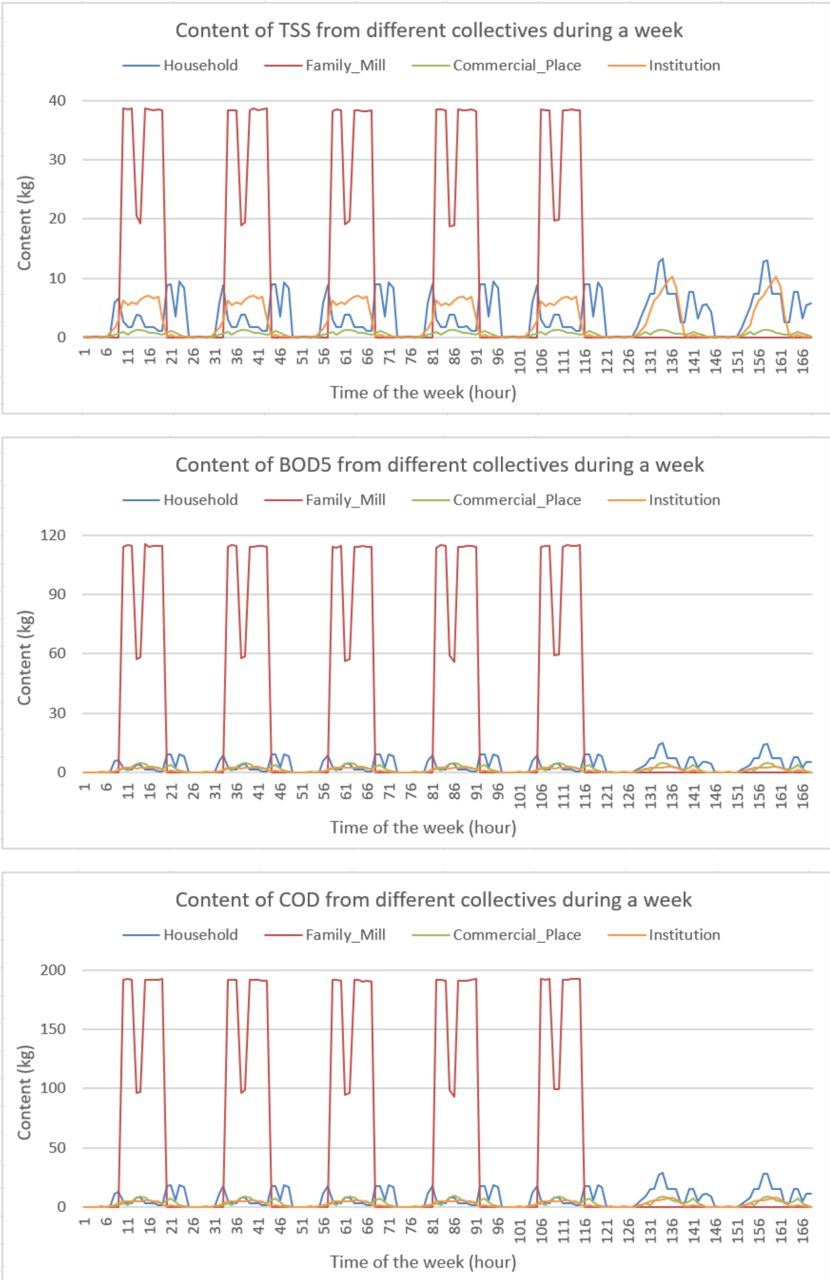


Figure 5.5: contents of wastewater quality indicators from different collectives

5.1.2 COMPARISON AMONG HOUSEHOLDS

In terms of the generation of household wastewater, the results of various comparisons among all families are presented here. Such comparisons include: the comparison among family groups (namely blocks), as well as the comparisons among individual families regarding total household wastewater production and the production by a single water-use practice.

1) Comparison among family groups (blocks)

A residential block contains multiple households, thus the household wastewater production of a block is the sum of the productions of all households within the block. Figure 5.6 shows the histogram of the average hourly household wastewater production at each residential block. The blocks in the histogram are sorted by their production values from the largest to the smallest, with a smooth decreasing trend. It can be also found that 6 blocks (about 10% of the total blocks) account for around 28.3% of the total household wastewater quantity. If such information can be combined with the locational information of the blocks, the local government will be clear of where it should focus mainly on to reduce the household wastewater amount.

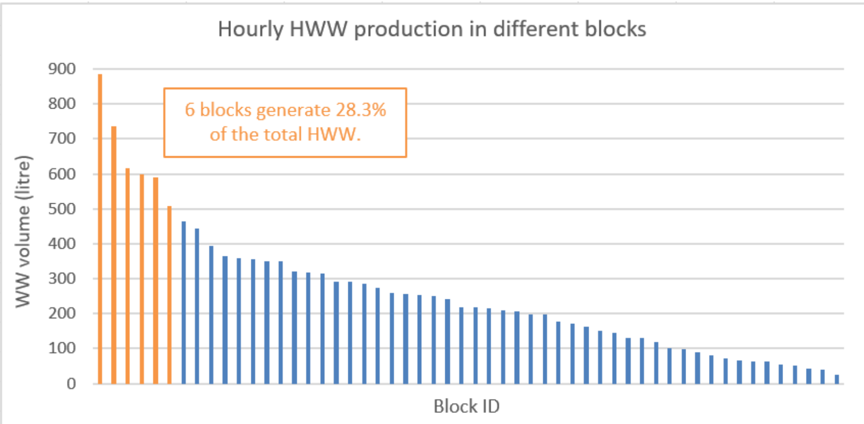


Figure 5.6: histogram of the average hourly HWW production at different residential blocks

2) Comparison among individual families regarding total HWW production

The volume of wastewater produced at home varies from one family to another, so does the average production per person. Figure 5.7 depicts the histogram of the average hourly household wastewater production per person in individual families, sorted by descending. In general, the descending trend is smooth, and some important details can be detected. The largest value is 8.92 litre/hour/person from the family type of 'single family', while the smallest one is 3.75 litre/hour/person from the type of 'family without children'. To be more accurate, in single families, most of the values are very high, and very few are medium or low. Such distribution also applies to families with children. Contrarily, families without children are mostly located in the low-value area, and the larger the value, the fewer the number of families of this type. Meanwhile, the numbers of retired-couple families and young-couple families are few but still noticeable in the figure, and families of both types are almost distributed evenly in the middle-low-value range. Thus, it can be further deduced that if the local government considers improving the wastewater situation by changing individual behaviour, it should firstly think about the individuals in single families and families with children.

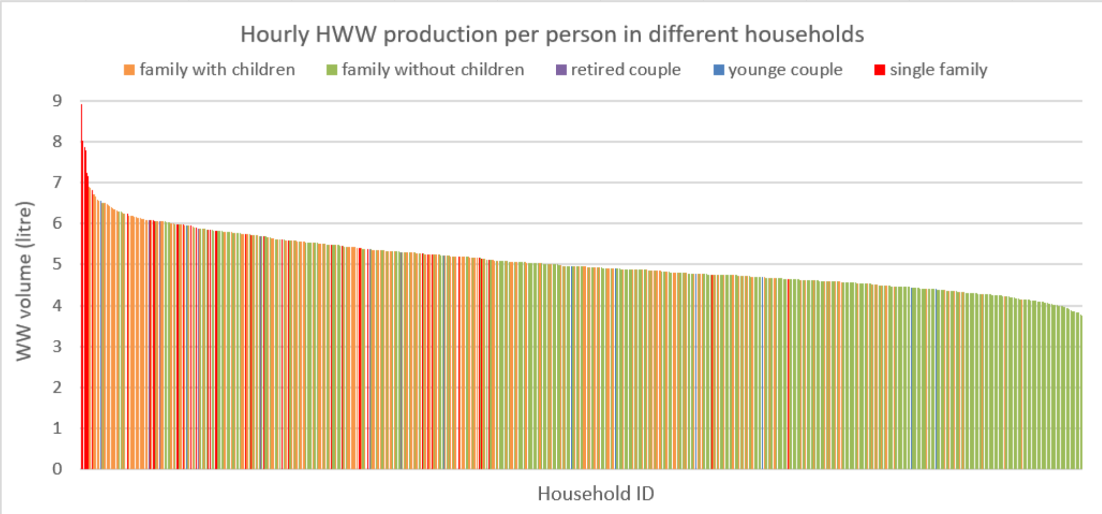


Figure 5.7: histogram of the average hourly HWW production per person in different families

3) Comparison among individual families regarding showering

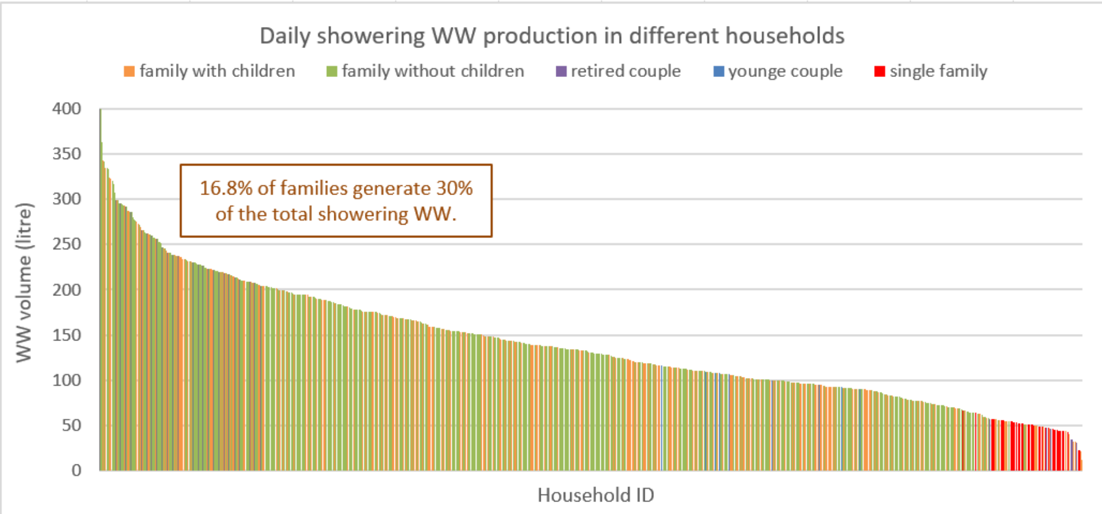


Figure 5.8: histogram of the average daily WW production for showering in different families

With regard to the wastewater generated by showering at home, its average daily production in each household is shown in Figure 5.8, sorted by descending. Generally speaking, 16.8% of families produce 30% of the total volume of showering wastewater. Besides, such productions of families with children are evenly distributed from low to high values, so do families without children. Values of retired-couple and young-couple families are mainly in the low-value range, while single families are all in the spectrum of very low values that is actually a mix of multiple family types with single families the most. Therefore, if a highly efficient shower head is going to be implemented in the local market, it will be most likely to become popular among families with the highest showering wastewater production, so it is recommended that such new technology should be widely advertised to families with children and families without children at first, instead of retired-couple, young-couple or single families.

4) Comparison among individual families regarding using washing machine

The average weekly amount of wastewater produced by using washing machines in every household is sorted by descending, as shown in Figure 5.9. The histogram is not smooth but serrated, this is because for a family, the amount of wastewater produced by the washing machine in a week is determined by the times of usage and the production of using the machine once that relies on the technical parameters of the machine itself. Generally, 21.9% of families generate 30% of the total amount of washing-machine wastewater. To be more specific, the productions of families with children are mostly located in high-value places, with the rest in the middle-value area. Values of families without children span the whole range, but a large majority of them are low and medium. Single families are still at the tail of the histogram, but more dispersive, not in a single spectrum, while retired-couple and young-couple families are distributed evenly in low and middle values.

Similarly, such finding suggests that if a more efficient mode of washing machine is going to be applied there, families with children should be taken as the first option to advertise, as they produce more washing-machine wastewater and more likely to install the new mode. Besides, due to the direct link between wastewater production and the technology of the machine, the efficiency of a new technology in reducing household wastewater production could be obviously verified if it is widely implemented in local families with children.

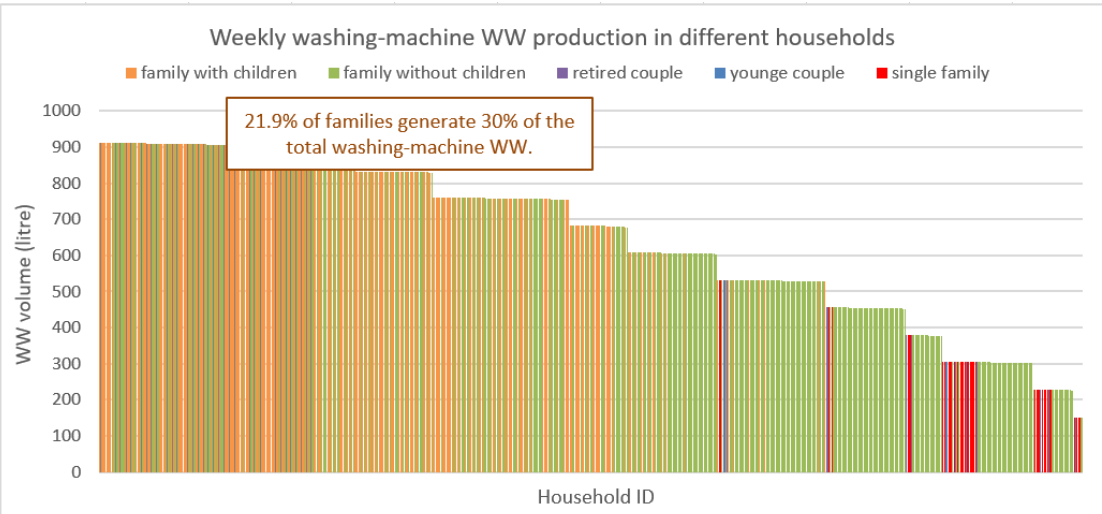


Figure 5.9: histogram of the average weekly WW production via washing machine in families

5.2 SENARIO ANALYSIS

Scenario analysis is designed to test the effect of different measures probably taken by the local government, e.g., organising a water-saving campaign in a certain place, thereby providing insights for future policies and actions in realism. For this purpose, a few experiments are conducted, including the tests for the optimal location and timing of a water-saving campaign. Such campaigns can boost the public awareness of saving water to reduce the total production of household wastewater.

5.2.1 LOCATION OF THE CAMPAIGN

This subchapter answers the question: *if the government is considering organising a campaign, then where is the optimal place for it?* Considering the most common situations of organising a campaign in the real world, this question can be further divided into two sub-questions as follows.

1) if the government considers a campaign within a single block, then which block is the best choice?

This sub-question relates to two groups of experiments, as all blocks have two definite attributes, e.g., the geographical location of the block and the number of households within the block. Thus, each group is used to test the importance of one property.

- If the geographical location of the block matters?

  The first group of experiments deals with the influence of the spatial location of the block where a water-saving campaign is held on public consciousness of saving water in the study area. For this purpose, three blocks with the same number of households (12 households) but in different locations (Figure 5.10) are selected to experiment on. In each experiment, a water-saving campaign is held in a certain block the 10^{th} week of the simulation run, and the value of public water-saving awareness is recorded at weekly intervals for 20 weeks. Thus, three time series of public consciousness are obtained and then compared with each other and also with the one of no campaign, as shown in Figure 5.11.

  It is clear in the second figure that there is a sizeable gap between the curves of holding a campaign and no campaign, but no evident difference among the three curves of having a campaign. That is to say, the results of experiments in which a campaign is held in the three selected blocks respectively are quite similar. Such findings confirmed that water-saving campaigns could indeed improve public awareness of saving water, and the geographical location of the block where such a campaign is organised is not an essential factor for impacting the effect of the campaign.

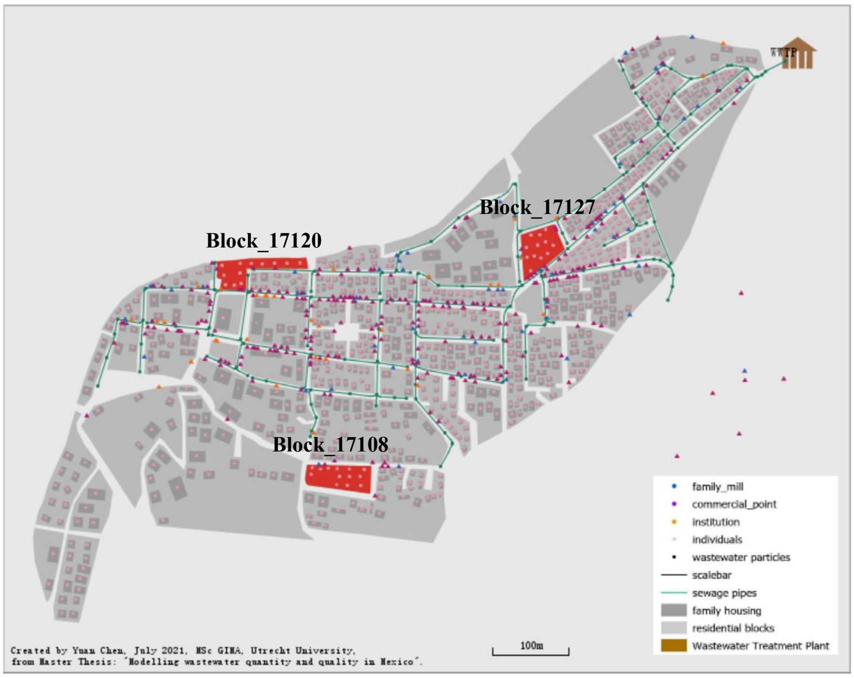


Figure 5.10: geographical location of the three blocks in comparison

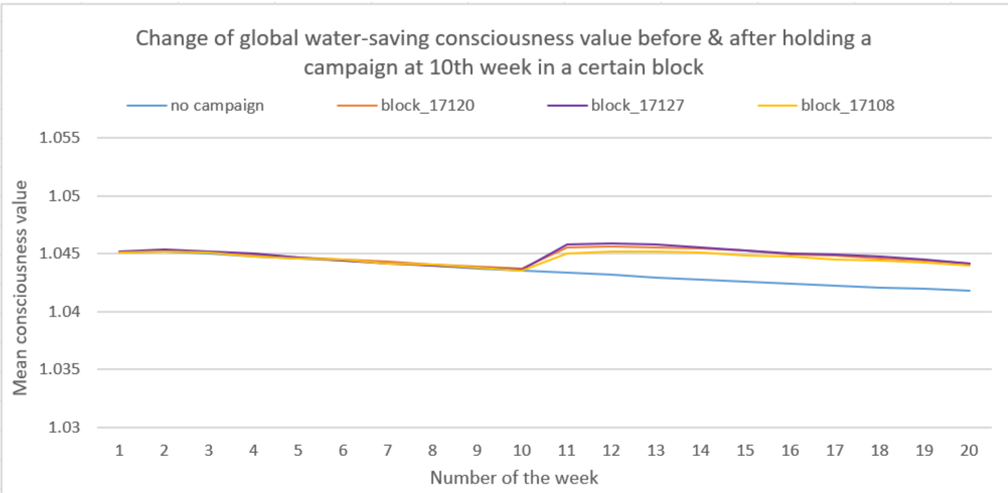


Figure 5.11: change of public water-saving consciousness without and with a campaign at the 10th week in selected blocks (with different location) respectively

- If the number of households within the block matters?

Another property of blocks in consideration is the number of households within the block. Its impact on the effect of a water-saving campaign is tested in the second group of experiments that selects three typical values of the number of households within a block, i.e., 11, 25 and 43 households, as shown in Figure 5.12. The curves in the figure represent the time series of public water-saving consciousness at weekly intervals for 20 weeks with no campaign and with a campaign held at the 10th week in the corresponding blocks respectively.

Similarly, there is a clear gap between the curve of a campaign wherever it is organised and the curve of no campaign, which reinforces the conclusion about the effectiveness of such a campaign in raising public awareness of saving water. Meanwhile, it is also noticeable – the significant difference among the curves of a campaign held in blocks with different numbers of households, and that the more households the block contains, the higher the public consciousness value is. This finding leads to the conclusion that the number of households within the block where the water-saving campaign is organised really matters to the effect of the campaign, and the more the households, the better the effect. If such a campaign is held in the block with the most households (i.e., 43 households in the study area), it can produce the best outcome.

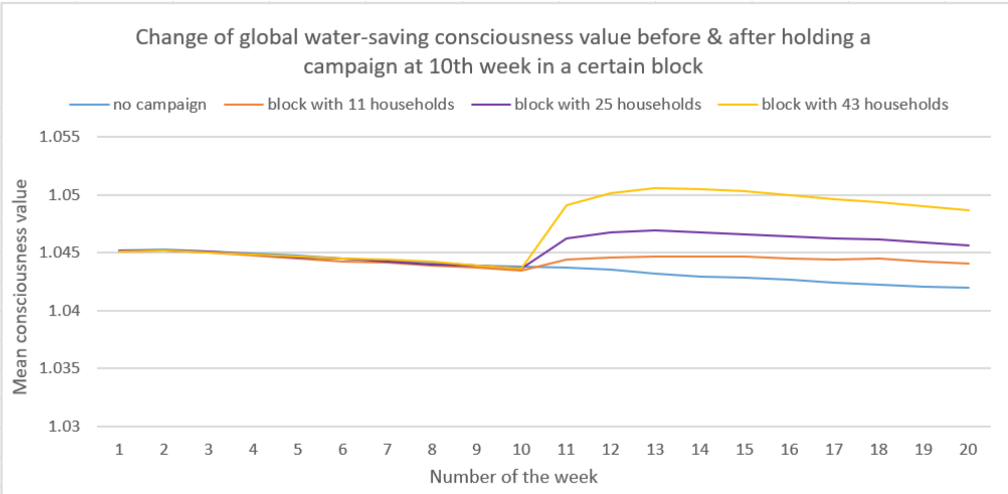


Figure 5.12: change of public water-saving consciousness without and with a campaign at the 10th week in selected blocks (with different numbers of households) respectively

2) If the government considers not only the block, but also other types of places, that is to say, the water-saving campaign could also be organised in such places as school and the area near the treatment plant, then where is the optimal place for a campaign?

In this case, three kinds of places are taken into consideration for organising water-saving campaigns, including *school*, *block*, and *the area near the treatment plant (TP)*. There are four schools in the study area, including a kindergarten, two high schools that have approximate numbers of students and staff, and a mixed school with multiple educational levels. Considering the campaigns in reality, one of the high schools is selected as the representative of the *school* type. Besides, the block with the most households and the area within 150 meters away from the TP are selected to represent their own place type, respectively. The geographical locations of the three places are shown in Figure 5.13, while Figure 5.14 compares the results of no campaign and conducting a campaign in each of the places at the 10th week, with each curve depicting the change of public water-saving awareness at weekly intervals for one year.

With no doubt, the three curves of holding a campaign have obviously higher values than the curve of no campaign after the 10th week, which verifies the significance of water-saving campaigns again. Then, the curves of running the campaign in the block and in the area near TP are quite close, and both are remarkably lower than the curve of school. That is to say, the campaign held at school can stimulate the public awareness to a higher level than that held in other places. Therefore, compared to blocks and the area near TP, school is the optimal choice for the government to organise a water-saving campaign. It is justifiable, because the campaign held at school can effectively enhance the water-saving consciousness of teenagers, affecting more households than the one held in other places. One additional finding is that the effect of a campaign reaches its peak around one month after it is organised, due to the spread of information.

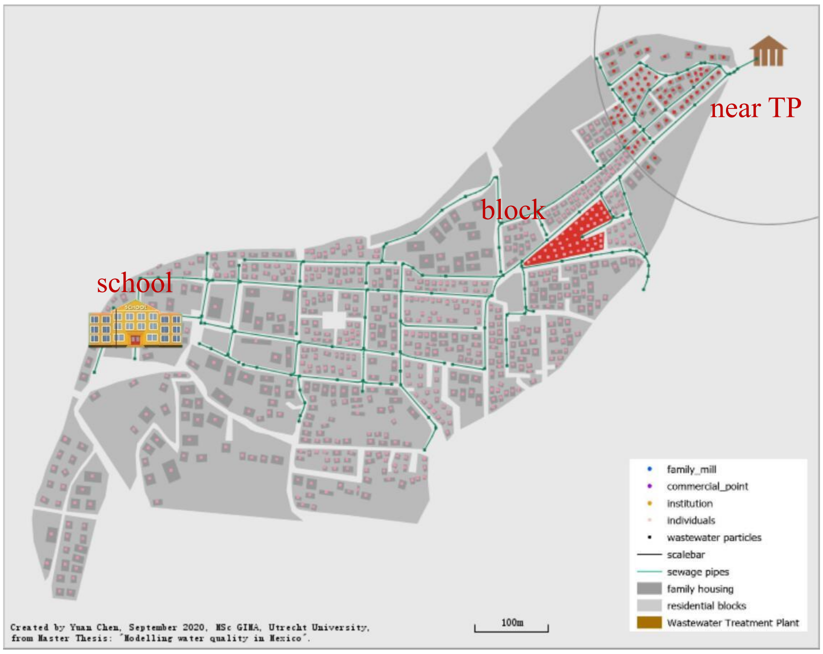


Figure 5.13: geographical location of the three places in comparison

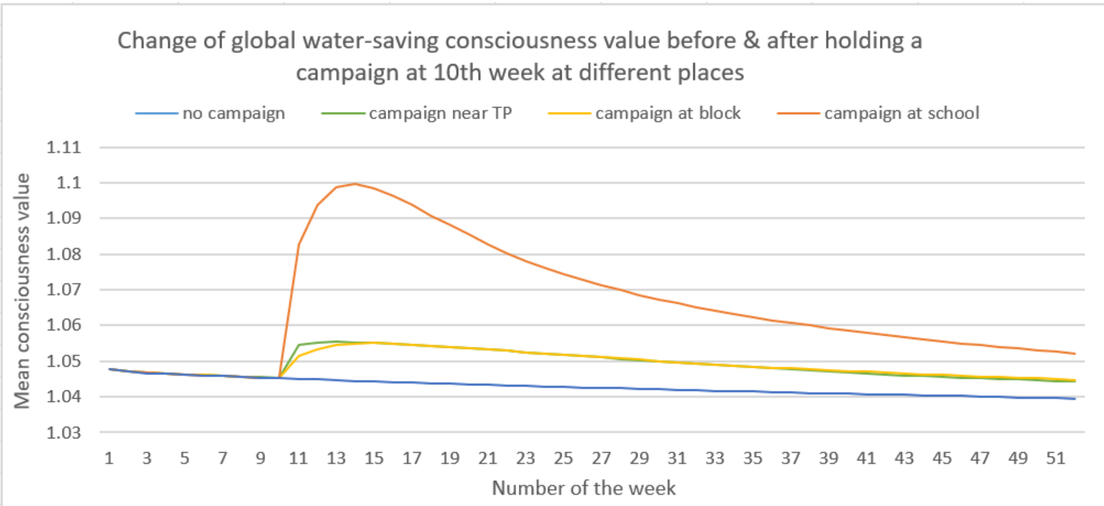


Figure 5.14: change of public water-saving consciousness without and with a campaign at the 10th week in selected places respectively

5.2.2 TIMING OF THE CAMPAIGN

This subchapter answers the question: *if the government is considering organising a campaign, then when is the optimal timing for it?* This question is highly linked to the influence of weather on human water-use activities, and is clarified by experiments in two successive steps.

1) Monthly variation in household wastewater production due to weather conditions

As elaborated in chapter 3.3.4 *Submodels*, weather plays an important part in the average daily frequencies of people using certain domestic devices. Accordingly, the behavioural pattern of an individual using water at home in a day varies with the weather condition of the day, so does its hourly water-use activities and the wastewater production at the household level. Over time, the average amount of wastewater per hour produced by all households differs significantly from one month to another. Figure 5.15 gives a general picture of the weather conditions (in terms of temperature and precipitation) in different months of the year, and their according average hourly HWW production. The temperature pillar (blue) refers to the average daily temperature of the month, while the precipitation pillar (green) means the number of rainy days in the month, and the (red) curve of HWW volume links the points one by one that show the average household wastewater production per hour at each month.

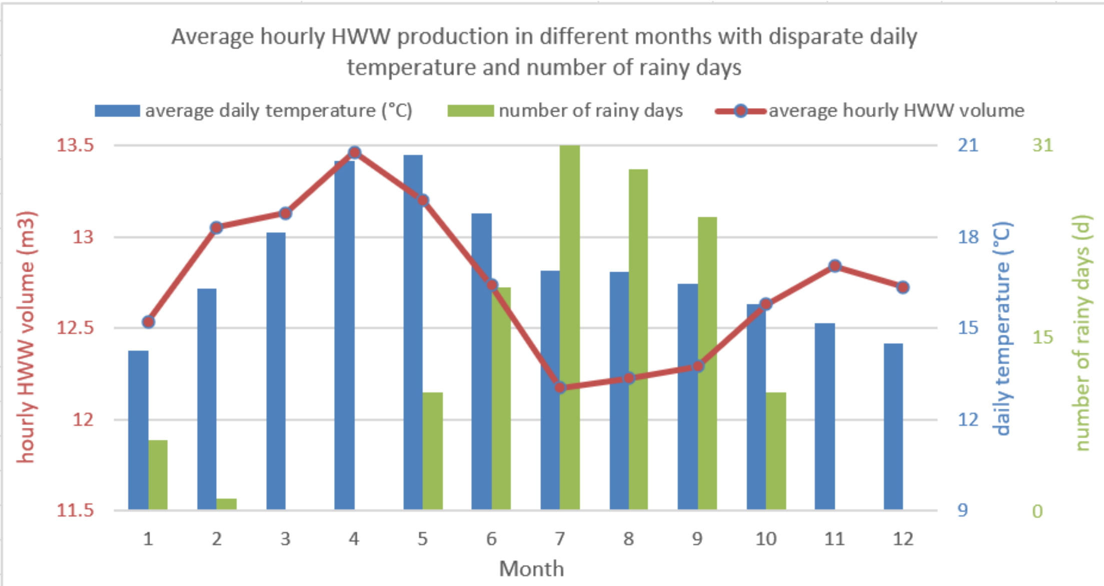


Figure 5.15: monthly weather conditions and average hourly HWW production

In general, the trend of average hourly HWW volume is almost consistent with that of average daily temperature, as the temperature is the main climate factor compared to the precipitation that is responsible for the minor fluctuations in HWW production. The month with the lowest hourly production is July, whereas the one with the highest value is April. The production (red) curve starts with a sharp rise from January to April, but soon drops rapidly until July, followed by a subtle growth in the succeeding two months, and afterwards experiences a remarkable increase in October and November, ending with a slight decrease in December. Therefore, the conclusion is confirmed that weather conditions, especially the temperature, are crucial factors for the monthly variation in the average hourly (total) HWW production. It's worth noting that this experiment result presents the hourly HWW productions in different months only under the influence of weather conditions, instead of real values that, in real life, are also affected by other social factors, such as the summer holiday and the Christmas holiday.

2) Effects of starting a water-saving campaign in different months

As demonstrated above, the change in monthly mean weather conditions contributes to the variation in the average HWW production between months. Thus, it is easy to infer that if the month when the water-saving campaign is held changes, the long-term effect of the campaign on reducing the total HWW production may vary significantly. This inference is verified by the experiments of the second step that test the cumulative reduction effect of a water-saving campaign held in different months during a whole year (assuming that the campaigns are all held in the same size and location), and thus identify the optimal timing (the month with the maximum effect) for such a campaign.

The experiment result is shown in Figure 5.16, containing 12 subfigures. Each subfigure compares two curves, one connecting the average hourly HWW production in the 12 sequential months of the corresponding test year under the scenario with no campaign, while the other showing the same thing but under the scenario with a campaign held in the first month of the test year. Test years differ between subfigures, starting from different months and exactly spanning 12 months, but they are the same for the two scenarios in the same subfigure. In this way, the reduction effect of the campaign held in a certain month can be measured by the difference between the two curves in the subfigure where the test year starts from the month in study. For instance, the effect of the campaign in January is obtained by comparing the curves in the subfigure in which the test year starts from January.

It is apparent that the trend of the curve with no campaign in these subfigures differs from each other and from the result in the subsection above. This is because each month starts with different weekdays or weekends in different test years. For instance, January naturally begins with Monday in the test year starting from January, but with Thursday, if the test year starts from December. That, combined with the vast difference in HWW production between weekday and weekend, leads to unequal HWW amounts for the same month in different test years (subfigures). Another noticeable feature found in all subfigures is that the difference between the two curves from the same subfigure is the largest in the first simulation month, and becomes smaller over time, finally close to 0 after 9 months. The reason behind it can be that public awareness normally surges when a relevant campaign is held around them, and then declines gradually as time goes by.

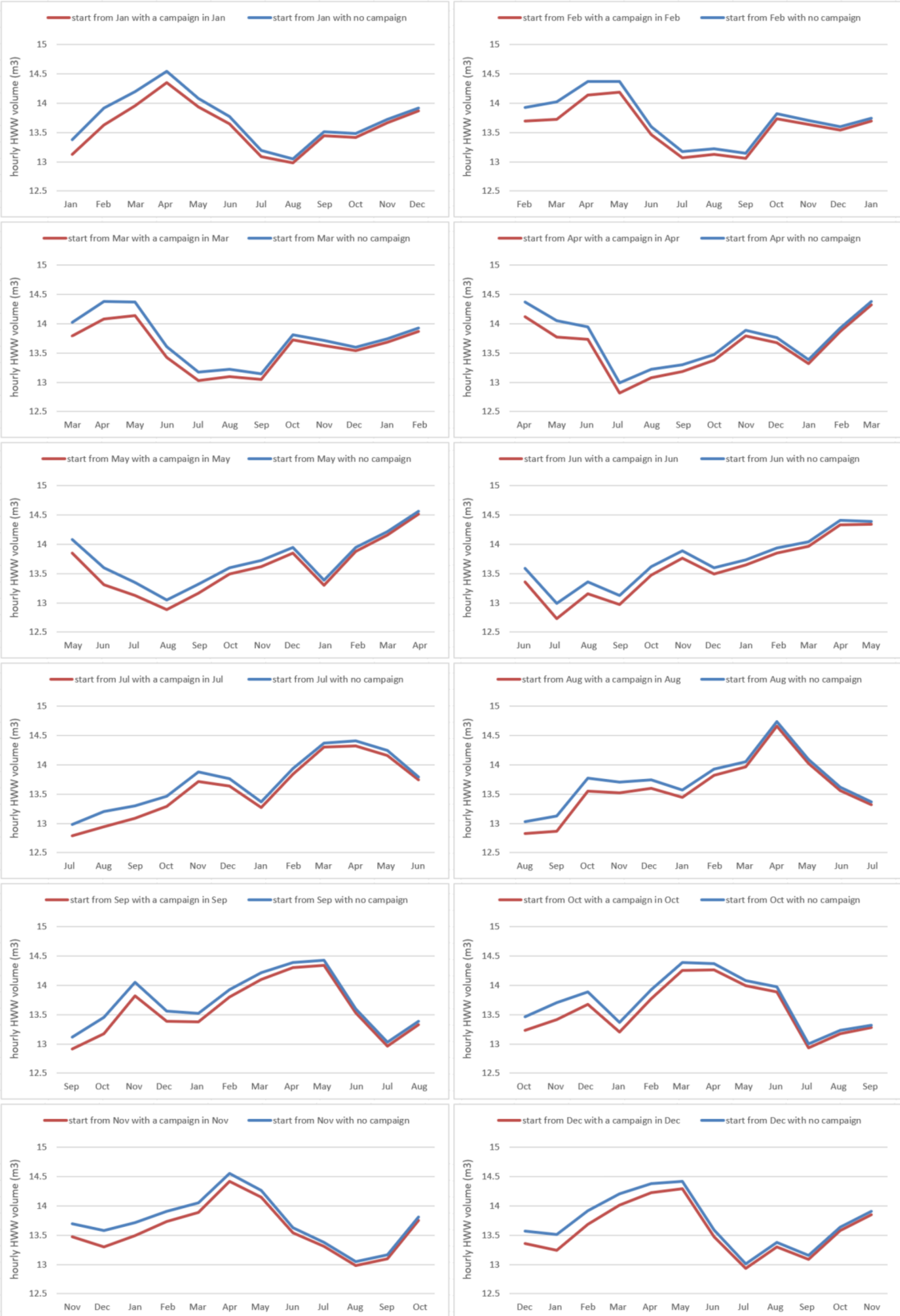


Figure 5.16: Average hourly HWW production (m3) in different months during a year

To compare the reduction effect of the water-saving campaign held in different months in a more intuitive way, Figure 5.17 is made based on the subfigures above. Each pillar represents the average daily volume of the reduced HWW caused by the campaign held in the corresponding month. Here, it is quite clear that the campaign in March produces the best effect on reducing HWW production, but on the contrary, the campaign in August seems to have the least impact on HWW reduction. The reason might have to do with the finding in Figure 5.14 that public consciousness reaches its peak one month after the campaign is organised, and the conclusion of Figure 5.15 that the average hourly HWW production is the highest in April. In other words, if the campaign is held in March, the public awareness of saving water can reach its highest value in April that is exactly when people produce HWW the most, so the total reduced volume is fairly likely to be the largest compared to the campaigns held in other months. Therefore, it can be concluded that under the same conditions (mainly the cost) of organising a water-saving campaign, the best timing for it is March, as the effect of the campaign to reduce the total HWW volume is maximised in that case.

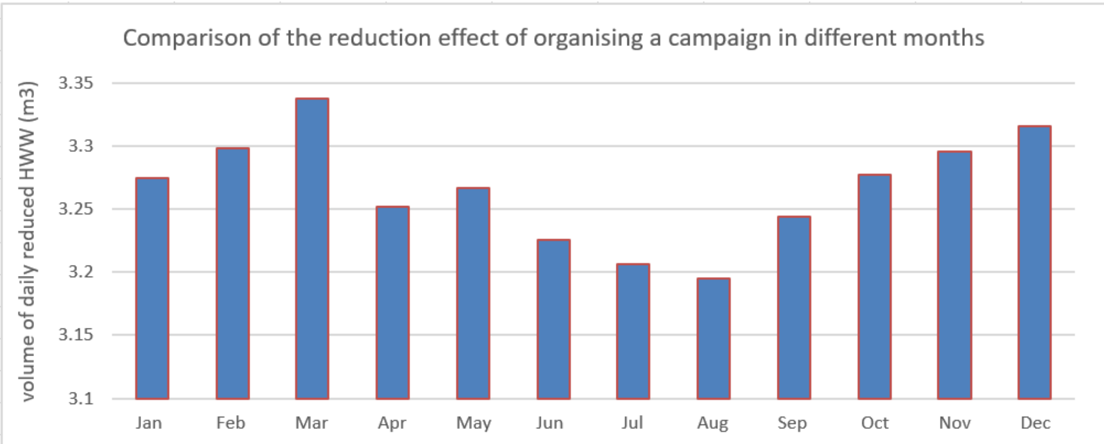


Figure 5.17: Daily volume of reduced HWW with a campaign held in different months

6 CONCLUSIONS AND DISCUSSIONS

6.1 CONCLUSIONS

The thesis mainly focuses on implementing an agent-based modelling method in simulating the variation of wastewater quantity and quality over time and space in an urban context. The key findings and main conclusions of this research corresponding to the three research questions described in Chapter 1 and can be summarised as follows:

RQ1: How can we model wastewater generation and flow in the catchment?

- Which basic elements are included, and how do they interact with each other and the environment? (in terms of the wastewater quantity)

  Just as in the real world, sewage is generated by human behaviour, and the only type of agent created in the model is the individual. All agents are assigned with multiple attributes, e.g., age, educational age, and water-saving consciousness, and different combinations of water-use practices as their behaviour. An agent's behavioural pattern is mainly determined by its age attribute and fluctuates with its water-saving consciousness value that is highly related to its educational age (that is, years of being educated).

  First, children who are defined as individuals at the age spectrum of 0 – 5 years old are only attributed with the practices of using the bathtub, the toilet, and the washbasin. Teenagers who are between 6 – 15 and adults at 16 – 59 have the practices of using the same three devices plus the shower, whereas seniors who are over 60 years old only use the toilet, the washbasin, and the shower. Then, such classification of individuals (the classification by age) also basically decides the daily frequency and time slots of individuals using each of these devices. For instance, teenagers and adults may take a shower in the morning before going out for school/work or in the evening before going to bed or both, whereas the use of washbasin is evenly dispersed in the daytime, with far less use at night.

  The daily frequency of using each device is determined based on statistics of people's daily water-use activities and then adjusted to a lesser extent according to the type of the device user. For instance, the average use of the toilet for ordinary citizens is four times per day, but seniors are likely to use it more often, so the daily times of seniors using the toilet is set as the average value multiplied by 1.2. The exact values of basic use frequencies of all devices for each type of individual are explained in detailed in chapter 3, the section of *Submodels*.

Meanwhile, the real frequency of using a certain device on a certain day is also influenced by the weather condition of the day, i.e., the temperature and the precipitation. The hotter the weather, the higher the frequency of using the bathtub, the toilet, the washbasin, and the shower. Their relationships are exactly proportional functions, with parameters of each function determined by the precipitation condition (rainy or no-rain) of the day, which is also elaborated in chapter 3 the *Submodels* section.

On the other hand, the total wastewater production of an individual is also proportionate to the unit production of using each water-demanding device once. The basic value of the unit wastewater production of a certain device is derived from its technical parameters and statistics of people's water-use habits. For instance, the most ubiquitous outflow rate of a showerhead is about 9 litres per minute, and the duration for a shower is commonly 5 minutes, so the basic value of the wastewater production for using the shower once is set as 45 litres in the model. More basic values of using a device once are determined in chapter 4, section *Parameterisation*.

Based on the basic value, the actual wastewater production of using a device once also fluctuates with the water-saving consciousness of the user itself. The higher the consciousness, the lower the unit wastewater production of the individual using the device. This relationship is close to the inverse sigmoid curve, and such rule applies to the toilet, the washbasin, the shower, and the washing machine (for the whole family) as well as to all types of individuals, which is described in chapter 3, *Submodels*.

In addition, individual water-saving consciousness is not consistent throughout the simulation. The initial value is determined by the type of individual. Teenagers are created with a consciousness value of 1.1, whereas others have a consciousness value of 1.0. Subsequently, at each tick (an hour), the consciousness value of a person will increase to the highest value of its family members, including itself. Every 24 ticks (a day), the consciousness value will decrease by 1% of its current value when the current value is beyond its initial value; otherwise, it will remain the same. Every 168 ticks (a week), the consciousness value will be updated based on the values of the neighbours of the individual. When over 50% of its neighbours from the same family type have higher values than itself, it will go up to the average of the consciousness values of the neighbours with higher values.

Besides, individual consciousness can be enhanced by water-saving campaigns. Such campaigns can be organised at different locations, e.g., residential blocks and schools. If the campaign is held in a block, the individuals within the block will increase their own consciousness values by 0.03 (30%), 0.06 (30%) or 0.1

(40%) randomly, while if the campaign is in a school, only a certain number (equal to the school's scale) of teenagers who are randomly chosen will boost their consciousness values by 0.03 (30%), 0.06 (30%) or 0.1 (40%) randomly. The whole mechanism from initialising to making changes to individual water-saving consciousness is elaborated in chapter 3, *Submodels*.

- How to model movements of agents and collectives' behaviour?

During weekdays, individuals can belong to different collectives based on the time of day. An individual can belong to a household, then become part of a family mill, a commercial place (e.g., hotel and restaurant) or an institution (e.g., school, hospital, and museum) collective during working hours, and return to the household collective again. In this way, the same individual is at different locations at different hours and produces different quantities of wastewater. Like individual agents, collectives have a wastewater production behaviour.

The shift among the collectives that an individual belongs to is realised by the movement of the individual, which happens only on weekdays. All teenagers are supposed to go to school and adults who are employed have to be at their workplaces during working hours, whilst children and seniors are assumed to be at home at the same time. Working hours adopted in the thesis are the universally recommended working hours; namely 9:00 am to 5:00 pm. For this purpose, adults are assigned with one more attribute: employment, indicating if the adult has to go out for work on weekdays, thereby showing the location (at home or at a workplace) where the individual is at a certain hour.

On the contrary, on weekends, most families stay at home, and only a very small proportion of local residents go out for relaxation. In the thesis, the wastewater produced by stay-home individuals is aggregated to the household collective, whereas the wastewater generated by going-out families is not literally included in the total wastewater production of the study area, but the wastewater from collectives that still generate wastewater on weekends (such as restaurants, libraries, etc.) partially implies the wastewater production of such families.

For another thing, there are four types of collectives (i.e., households, family mills, commercial places, and institutions) that are designed with disparate behavioural patterns regarding wastewater production. Household collective's behaviour are the simulation of families using the kitchen sink and the washing machine, with its patterns of generating wastewater conform with the real-world situation of cooking (at lunch time and dinner time) and washing clothes (mostly on weekends with a few on weekdays). The values of the average wastewater production per person for (preparing and cleaning after) a meal are collected from the report of people's water-use habits, while the unit production of using the washing machine once depends on the technical parameters of the appliance – the most prevalent model of washing machines in the local area.

In contrast, the behavioural pattern of the family mill collective is consistent with the wastewater-production pattern of its manufacturing process, which is assumed to be a stable curve during working hours with a sag at lunch time. All family mills follow the same pattern, but the average values of their hourly wastewater production differ remarkably due to the diversity of their type and scale attributes. The type of mill is determined by the type of its products, e.g., flour mill and lumber mill, which decides how much wastewater is generated for manufacturing a unit of products, while the scale of the mill refers to the number of its products within one hour. The data relating to the former factor are collected from literature, while the information on the latter is provided by the supporter of the thesis project. The exact values of all corresponding parameters are listed in chapter 4, section *Parameterisation*.

Behaviour of commercial place and institution collectives simulates the wastewater generation in socio-economic processes in commercial places (profitable) and institutions (non-profitable). Unlike the family mill collective, the behavioural pattern of a commercial place collective varies with its type (i.e., restaurant, hotel, bar, and retail store). Moreover, its average hourly wastewater production is also determined by its type and scale attributes. The scale here means the number of visitors to the place every hour, while the type decides the average wastewater production per visitor. For instance, a restaurant collective has a distinct pattern and hourly wastewater production than a hotel. Such rule also applies to different institutions (i.e., school, clinic, hospital, public toilet, municipality, and museum/library). The wastewater-production patterns of each type of these places and the determination of all related parameter values are elaborated in chapter 4, section *Parameterisation*.

- how can the wastewater quality be assessed?

The contents of TSS, BOD5 and COD are the most common indicators used to evaluate the quality of wastewater. The thesis introduces the same indicators to assess the quality of the wastewater generated in the study area. However, because of the COVID-19 pandemic, the quality of wastewater at any point cannot be sampled, so the contents of the three indicators in wastewater from different provenances are ascertained based on literature. For instance, the TSS concentration in household showering wastewater is commonly 150 +/- 50 mg/litre, whilst the COD concentration of the wastewater from textile/dying industry is around 1505 mg/litre. Such values only exhibited the average level across the world, rather than the exact condition of the study area, listed in chapter 4, section *Parameterisation*.

Meanwhile, the wastewater quality at any other spatial location, namely the points inside the pipelines, instead of those wastewater provenances, at a certain time is just the physical combination of the wastewater that is passing through, with no consideration of biological or chemical reactions among the substances in wastewater. The overall quality of the wastewater inflow to the treatment plant at each hour is the physical aggregation of the wastewater reaching the plant at the hour from multiple provenances. In this sense, the result of the wastewater quality modelled in the thesis is just an approximate case of the real-life condition of the study area. Corresponding equations are explained in detail in chapter 3, section *Submodels*.

- How to model the flow of wastewater in pipelines?

  To simulate the flow of wastewater in pipelines, a new agent type is created in the model: wastewater. Each wastewater agent represents a wastewater particle with the following attributes: volume and velocity. Volume means the amount of wastewater represented by the wastewater particle, while the velocity refers to the movement speed of the particle inside the pipeline. The former attribute is consistent throughout the life of the agent, while the latter varies with the pipeline. The agent's velocity equals the velocity of the sewer pipe it is lying in that is calculated based on the Manning's equation, taking the slope, the diameter, and the material of the pipe as the formula's inputs.

  In this way, the flow of wastewater in pipelines is realised by the movement of wastewater agents along the pipeline. When moving, each particle is regarded as a closed iron ball, with no biological/chemical reaction nor interaction nor physical conflict with others. At each tick, every wastewater agent moves forward at its current velocity, following the direction of the pipe it lies in. If the distance from its current location to the next pipe node is less than its current speed, it will first reach the node at the current speed and then change its direction and velocity based on the following pipeline and continues moving forward the rest time at the new speed. Once the agent reaches the treatment plant, it dies. The whole mechanism regarding wastewater agents' movement is elaborated in chapter 3, section *Submodels*.

RQ2: How can we validate the model?

Because of the COVID-19 pandemic, the plan of in-situ data collection was temporarily cancelled, resulting in the lack of data regarding the real-time wastewater inflow to the treatment plant and its quality. Thus, the validation of the model cannot be realised by comparing the model results with actual monitoring data, but only with the results of previous research.

- In terms of wastewater quantity

  Several data sources are cited in the thesis to be compared with the model results in terms of wastewater quantity. The items in comparison are all at the aggregate level. First, the blueprint of rehabilitating the sewer pipe network of the study area provides the value of the approximate household wastewater production per capita per day there which is 120 litres/cap/d, while the counterpart of the model results is 120.091 litres/cap/d. Then, the work of AybuĞa & IŞildar (2017) is introduced to calibrate the composition of household wastewater which means the proportions of the wastewater through different domestic devices accounting for the total household wastewater production. Both the previous work and the model results show that showering produces the most (29%), followed by the washing machine (21%) and the toilet (20%).

  Subsequently, the daily pattern of household wastewater production illustrated in the research of Gato-Trinidad et al. (2011) is compared with the model results of the thesis. Both results show a similar trend of the daily production pattern and the same time slots for peaks and basins in a day. Besides, the composition of the total wastewater production, meaning the proportions of the wastewater from different collectives, is verified by the report of the Asia-Pacific Economic Cooperation regarding the wastewater condition in Mexico. The model results further confirmed the conclusion in the report that industry (meaning family mills here) contributes almost 40% to the total wastewater production, and domestic uses (including the water uses in households, commercial places, and institutions) account for the rest, namely 60%.

- In terms of wastewater quality

  The regional wastewater quality depends on the detailed composition of the wastewater in the local area, thus it varies from one area to another. There is no in-situ monitoring data nor existing research regarding the wastewater quality of the study area, thus no validation work is done for the wastewater quality part of the model.

RQ3: How can this model be used to design different government strategies for controlling the quantity and quality of wastewater?

The government plays a significant role in controlling the local wastewater production. Individual wastewater production highly relates to their water-saving consciousness, whereas the government can boost the public awareness of saving water by many means, such as organising water-saving campaigns. The thesis did repeated experiments to test the effect of a campaign held at different places and timing on reducing the total household wastewater quantity.

- Should a campaign be launched via blocks or schools?

  The experiments on the campaign in different residential blocks found that the number of families within the block is the crucial factor influencing the campaign's effect, but the block's location does not matter. However, even compared with the block harbouring most families, the campaign held in a (primary/high) school performs much better to boost public awareness. Therefore, the school is the better choice to organise the water-saving campaign than the residential block, assuming that the cost for a campaign is the same no matter where it is organised. This may be because a school comprises hundreds of teenagers, thus covering more families than a single block, and more families enhance their water-saving consciousness at the same time.

- When is the best timing (month) for a campaign?

  Because weather conditions have an impact on individuals use frequencies of household devices, repeated experiments are conducted to test the effect of the campaign held at different month. The experiment results indicate that there is a slight variation in the average hourly wastewater production in different months of the year, and the campaign held at different months can lead to a reduction in the total wastewater production during a year to different degrees. Compared to other months, holding a campaign in March can bring about the maximum reduction.

  To sum up, a water-saving campaign is always effective in boosting the public consciousness of saving water, thereby reducing the total household wastewater production, but the location and the timing of the campaign can have an impact on its effectiveness. The experiment results suggest that if the government plans to hold a campaign, the best strategy would be to organise it at school in March, yielding about 3.35 m^3 reduction in household wastewater production every day.

6.2 DISCUSSIONS

1. Conformity with other results from literature

   The model results conform with the results from other research. For instance, the work of Domene & Saurí (2006) showed that the increase of individual awareness in saving water can result in a daily reduction of 4.3 - 4.6 litres per person in terms of wastewater production. The model also gets the similar results, with the reduction effect of an increase in individual consciousness being 3.6 - 7.1 litres per person per day.

2. Model design regarding individual consciousness

Individual consciousness regarding water conservation is difficult to measure and quantify, thus the consciousness value adopted in the thesis is only a qualitative indicator. The consciousness value of ordinary people is set to 1.0, indicating the average level of individual intention to save water. The stronger the intention, the higher the consciousness. Meanwhile, an upper threshold 1.5 and a lower threshold 0.5 are reasonably set for the indicator, just showing the limitation of increasing and decreasing the value.

3. Teenagers' role

On the one hand, teenagers are created with a higher consciousness initial value 1.1, compared to the initial value of other types of individuals 1.0. On the other hand, all family members will be assimilated to the highest consciousness value of themselves. Thus, it can be found that the consciousness value of other family members is dominated by the value of the teenager in the family. As a result, teenagers have a higher weight in terms of increasing the public awareness of saving water, which could partly explain why the campaign in school has the best effect of boosting the public consciousness.

4. Scalability of the model

The model is built with high scalability, meaning that the model could be easily adjusted to fit the condition of another catchment area. The modelling methodology is applicable for most cities, and the particularity of the study area is only determined by the parameters in the model. Thus, just by changing certain parameter values, could the model suitable for one region be easily reproduced to simulate the wastewater quantity and quality over space and time of another city. Moreover, the value of parameters can be easily changed on the user interface of Netlogo.

5. Government concerns

The aim of the Municipality (Government) is to keep the treatment plant in good order. There are two factors that influence this: reducing the total volume of wastewater produced and avoiding peaks in wastewater production. It is unclear at the moment which of these two strategies has the higher impact on the functioning of the treatment plant. It would be nice to have one combined metrics to optimise the model.

6.3 RECOMMENDATIONS FOR FUTURE DEVELOPMENT

There are some other aspects of the proposed methodology that could possibly be improved. A few potential research directions are listed for future investigation:

1. Data

There are two types of data to collect:

- survey data on individual water-use habits and consciousness

  Water-use habits of different types of individuals, including the pattern and daily use frequencies of domestic devices, are built based on the worldwide average level, not specific for residents in the study area. Accurate information about the water-use habits of local people, and the relationship between their habits and their family and personal characteristics, as well as the influence of weather condition, can only be gained by and analysed from surveys. Such data could help adjust certain parameter values in the model to make the simulation closer to the condition of the study area.

  Besides, data on consciousness of the population is also missing in the thesis, so such questions as how individual water-saving consciousness change over time, how the daily interaction among people affects their own consciousness values, what the relevant influential factors are, and how consciousness impacts on wastewater production, are all based on either the assumptions that come from real-life experience or the literature. Such data of a local area can be more accurate if they can be collected by survey, thereby making the model more specific to the study area.

- monitoring data on water quantity and quality at different points

  The breakout of COVID-19 worldwide made it impossible to collect data in situ, and the lack of monitoring data, especially wastewater quality data, badly undermines the effectiveness of model validation. Therefore, a special attention should be put on the collection of such data in the future work, like the quarterly or hourly observations of the wastewater flow rate passing by any point of interest and its quality (concentrations of TSS, BOD5 and COD, etc.). For this purpose, sensors that are capable to monitor such indicators should be installed at target points, and the treatment plant entry should be definitely prioritised. Then the real-time monitoring series of the wastewater quantity and quality at the interesting points (especially the ones at the treatment plant) can be used to calibrate the model by comparing the spatio-temporal distribution of the wastewater quantity and quality of the model results with the monitoring data.

2. Model development

The modelling methodology could also be further improved from following aspects:

- influential factors in consideration

  Human's behavioural patterns vary with their intrinsic personal characteristics and the exogenous environment, such as gender, age, religion, economic status, and the influence from family members, as well as the weather. However, because of the lack of certain data, not all influential factors are considered in the model. The one worth noting is the economic status of families. It was considered in many research as the factor that has an impact on people forming their daily water-use habits. Thus, it is highly recommended to include these missing but important factors in future modelling, and to figure out the exact quantitative relationship between these factors and the daily wastewater production patterns of individuals.

- stochasticity

  Stochasticity exists in the decision-making process of people on conducting a water-use activity or not. The observer of the model only gives the probability of an individual doing a certain activity at a certain time, thus if the individual adopts the activity or not is not totally deterministic but stochastic. However, the activity probabilities in the model are simply defined to follow the uniform distribution. Therefore, the future work is recommended to further explore and test other probability distributions of an individual's decision to do an activity at a certain moment, for example, the normal distribution, thereby fitting better the real-life occasions when people are making decisions.

- calculation of the flow rate

  In the thesis, the wastewater flow inside sewer pipes is computed by a simplified method: treating it as a group of discrete solid particles with no physical nor biological nor chemical interactions, which is actually not rigorous enough. The flow of fluids inside a pipe is actually much more complex, especially for wastewater which contains a variety of substances. Not only chemical and biological reactions among certain pollutants and virus, but also some physical phenomena may occur, such as infiltration and adhesion to the pipe wall. Thus, a deeper exploration of the actual situation of wastewater flowing inside the pipe is suggested to be conducted in the future research.

- temporal resolution

  This is a question that can be easily ignored, but quite important. A fine temporal resolution leads to more uncertainty and higher computational cost, whereas a rough resolution fails to reflect the real-time change of wastewater production with high accuracy. This thesis adopts the hourly temporal resolution. However, the wastewater generated at any place in the study area can reach the treatment plant within one hour, thus a finer resolution could help understand the peak hours of the wastewater inflow into the treatment plant which differ from the peak hours of production. On the other hand, the current resolution also makes it impossible to include some social dynamics, such as the increase in the total population and the rise in average income. Thus, according to diverse objectives of the future research, more temporal resolutions could be employed.

3. Optimisation of treatment plant

The model does not include the metrics to calculate the performance of a treatment plant. Thus, when we are comparing the effect of different strategies, it is hard to define which one can best benefit the treatment plant, thereby improving the efficiency of wastewater treatment. The thesis regards the strategy of avoiding peaks and reducing wastewater as the best artificial intervention for optimising the performance of a treatment plant, but it is not completely the actual case. In the future work, more knowledge about how the treatment plant function should be studied to better plan and design potential strategies.

4. Participatory modelling

Successful treatment of wastewater is always not the outcome of efforts from one single part. It is a collaborative work involving many sectors, including the government, the academia, and technical companies, etc. Seeking for the chance of collaborating with the local government could help further improve the model, at least in calibrating the relationship between public consciousness and the reduction in wastewater production. Meanwhile, such collaboration makes it possible to design and test more strategies based on the needs of the government, such as rising the water rates to different degrees. On the other hand, the model can provide guidance on how to optimise water uses and wastewater treatment across the entire city based on simulation results, thereby maximising the practical value of the model.

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APPENDIX I

ODD + D protocol of the urban wastewater quantity and quality model

		Guiding Questions	This Thesis
OVERVIEW	purpose	What is the purpose of the study?	- to understand how the wastewater is generated by human activities in terms of quantity and quality, both in time and space, including the impact of external environment - to simulate the flow of wastewater along the sewage network - to explore which role the government plays in the process
		For whom is the model designed?	- for researchers who are interested in ABM and wastewater modelling - for government decision-makers who are interested in wastewater-related problems
	Entities, state variables and scales	What kind of entities are in the model?	- the environment: digital presentation of the study area, including the sewage network - two types of agent: individual (including four subtypes: child, teenager, adult, and senior), wastewater (particle) - four types of collectives: household, family mill, commercial place, and institution
		By what attributes are these entities characterised?	- sewer pipelines in the environment: material, slope, length, diameter, geographical location - individual: age, educational age, water-saving consciousness, the household ID it belongs to, employment (only for adult) - wastewater: volume, geographical location, moving velocity, moving path - household: geographical location, household size, household type, ID, wastewater production - family mill/commercial place/institution: geographical location, number of workers, type, scale, wastewater production
		What are the exogenous factors of the model?	- temperature, precipitation - water-saving campaigns
		How is space included in the model?	sewer pipelines, agents and collectives are all located based on their geographical locations that are from the coordinates in real world or calculated by a mathematical algorithm
		What are the temporal and spatial resolutions and extents of the model?	- hourly time steps for an entire year - 726 families, 2815 individuals, near 80 family mills, about 250 commercial and institutional establishments, one wastewater treatment plant
	Process	What entity does what and in what order?	- beginning of the day: exogenous factors update, individuals determine their behavioural patterns.

	overview &scheduling		- each hour: individuals do their water-use activities and produce wastewater, collectives also produce wastewater based on the time and their behavioural patterns, wastewater particles move forward toward the treatment plant along the sewage network
DESIGN CONCEPTS	Theoretical and empirical background	Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the levels of the submodels (apart from the decision model)? What is the link to complexity and the purpose of the model?	- no population dynamics - no technology upgrades - no biochemical reaction nor physical conflicts among wastewater agents - the speed of fluid inside a pipeline is determined by the Manning equation
		On what assumptions are the agents' decision model based?	- agents are bounded rational and their activities of water use are all reasonable, meaning that they use water only when they need to do so - teenagers go to school on weekdays - employed adults go out for work on weekdays
		Why is the decision model chosen?	- the decision model of individuals is based on the water use habits of people in real life and statistics and probability theory
		If the model is based on empirical data and where does the data come from?	- data used to define individuals' and collectives' behavioural patterns is collected from reports and literature - precipitation and temperature are real recordings searched on the internet - location of households is delineated from Google Map - data of other three types of collectives, and the attributes of sewer pipelines and residential blocks, are provided by the co-supervisor
		At which level of aggregation were the data available?	at the residential block level
	Individual decision making	What are the subjects and objects of the decision-making? On which level of aggregation is decision-making modelled? Are multiple levels of decision making included?	only at the individual level: individual agents make decisions on when they do what water-use activity
		What is the basic rationality behind agent decision-making in the model? Do agents pursue an explicit objective or have other success criteria?	no objectives, individual agents just make decisions based on their daily behavioural patterns.
		How do agents make their decisions?	basically, at each tick, individual agents decide their probabilities of doing each water-use activity, and then compare it with a random value generated by the system to make a final decision on doing the activity or not. The exact mechanism varies with the activity, and some are more complexed.
		Do the agents adapt their behaviour to changing endogenous and exogenous state variables? And how?	Yes, individual agents update their daily frequency of doing certain water-use activities based on the precipitation and temperature values of the day.

		Do social norms or cultural values play a role in the decision-making process?	Yes, cultural values of saving water and social norms for cleanliness help set the initial values of some parameters in the model at the beginning of simulation.
		Do spatial aspects play a role in the decision process?	No
		Do temporal aspects play a role in the decision process?	Yes, individual agents make decisions every hour. If the decision-making model is built at the daily or weekly level, the result will be quite different.
		To which extent and how is uncertainty included in the agents' decision rules?	the model can only pinpoint the daily frequency and the temporal span of doing each activity, but the exact time of doing the activity is decided by the individual agent with a minor degree of uncertainty.
	Lear ning	Is individual learning included in the decision process? How do they change decision rules over time as consequence of their experience?	No
		Is collective learning implemented in the model?	No
	Indiv idual sensi ng	What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions? Is the sensing process erroneous?	- individual agents can sense daily temperature and precipitation automatically and simultaneously. - wastewater agents can sense all attributes of the pipeline where they are to calculate their velocity.
		What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?	all state variables of an individual agent can be sensed by other individual agents from the same household and by the collectives they belong to.
		What is the spatial scale of sensing?	no spatial scales for sensing.
		Are the mechanisms by which agents get information modelled explicitly? are individuals simply assumed to know these variables?	Yes
		Are the costs for cognition and the costs for gathering information explicitly included in the model?	No
	Indiv idual predi ction	Which data do the agents use to predict future conditions?	No data
		What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?	No models
		Might agents be erroneous in the prediction process, and how is it implemented	No prediction functions
	Inter actio n	Are interactions among agents & entities assumed as direct or indirect?	direct
		On what do the interactions depend?	the interaction depends on the social relationship between the agents and collectives.

		If the interactions involve communication, how are such communications represented?	individual agents transfer their decisions on doing water-use activities to the collectives they belong to when they are making the decisions.
		If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?	No coordination networks
	Collectives	Do the individuals form aggregations that affect/are affected by individuals? Are these aggregations imposed by the modeller or emerge during simulation?	four types of collectives: household, family mill, commercial place, institution. All are imposed by the modeller.
		How are collectives represented?	they comprise a group of individuals, assigned with attributes and behaviour, and emerge at fixed time slots.
	Heterogeneity	Are the agents heterogeneous? which state variables and/or processes differ between the agents?	Yes, individual agents and wastewater agents are both heterogeneous in terms of any of their state variables.
		Are the agents heterogeneous in their decision-making? which decision models or decision objects differ between the agents?	Yes, the decisions on water-use activities made by individuals vary with their attributes, following the same decision-making model.
	Stochasticity	What processes (incl. initialisation) are modelled by assuming they are random or partly random?	a minor degree of stochasticity is involved in the initialisation process of individuals and also in the decision-making process of individuals.
	Observation	What data are collected from the ABM for testing, understanding and analysing it, and how and when are they collected?	- the time series of hourly wastewater inflow and quality to the treatment plant. - the time series of hourly wastewater production and quality from different types of collectives
		What key results, outputs or characteristics of the model are emerging from the individuals?	the change of public water-saving consciousness that is actually the mean of all individuals' water-saving consciousness values
DETAILS	Implementation	How is the model implemented?	in Netlogo 6.1.1.
		Is the model accessible? if so where?	Yes, see the link in Appendix II
	Initialisation	What is the initial state of the model world, i.e. at time t=0 of a simulation run?	individual agents are generated from statistical data via a synthetic population generation step. As for the initial values of model parameters, see Chapter 4.2 Model parameterisation
		Is the initialisation always the same, or is it allowed to vary among simulations?	the initialisation of individuals may change a bit, as the synthetic population generation step involves a minor degree of stochasticity, while the values of model parameters remain the same.
		Are the initial values chosen arbitrarily or based on data?	based on statistical data and literature.
	Input Data	Does the model use input from external sources, such as data files or other models, to represent processes that change over time?	Yes, the data of the location and attributes of blocks, sewer pipelines and collectives are imported from Arcgis files, while the data of precipitation and temperature is read from .xlsx format files.

	Sub mod els	What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'?	see chapter 3.3.4 Submodels
		What are the model parameters, their dimensions, and reference values?	see chapter 4.2 Model parametrisation
		How were the submodels designed or chosen, parameterised, and then tested?	see chapter 3.3.4 Submodels + chapter 4.2 Model parametrisation.

APPENDIX II

You can find the complete file of the model in the following link:

https://drive.google.com/drive/folders/1vQRB_4T093Eqf4lkdl_mDOPvuU5kBIBE?usp=sharing

Instructions of using the model:

1. download the software Netlogo 6.1.1 via the link:
Download NetLogo (northwestern.edu)

2. download the folder containing the model and the data via the link:
https://drive.google.com/drive/folders/1vQRB_4T093Eqf4lkdl_mDOPvuU5kBIBE?usp=sharing

3. open the 'wastewater.nlogo' file with Netlogo.

4. follow the steps of 'Run the model' on the model interface, and enjoy running.

Note: errors might occur if other versions of Netlogo are used.