


Development of a Planning Approach for Resource Recovery and Reuse on Small Islands

Indra Firmansyah

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Propositions

1. A future proof sanitation planning approach including resource recovery and reuse is needed to establish a circular nutrient management.
(this thesis)
2. In assessing sanitation concepts, it is necessary to use environmental, technological, socio-cultural and economic sustainability indicators.
(this thesis)
3. Adaptation and mitigation should be combined to reduce climate change risks.
4. Self-sufficiency of agricultural production is hindered by consumerism.
5. Online meetings improve working efficiency not time efficiency.
6. Policy makers define the future not scientists.
7. A herd immunity from Covid-19 can be developed with strong vaccines.

Propositions belonging to the thesis, entitled

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Indra Firmansyah

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Thesis committee

Promotor
Prof. Dr Grietje Zeeman
Personal chair at Environmental Technology
Wageningen University & Research

Co-promotors
Dr Marc Spiller
Post-Doc, Department of Bioscience Engineering
University of Antwerp, Belgium

Dr Gerrit-Jan Carsjens
Assistant Professor, Landscape Architecture and Spatial Planning
Wageningen University & Research

Dr Frank de Ruijter
Scientist Farming Systems, Agrosystems Research
Wageningen University & Research

Other members
Prof. Dr W de Vries, Wageningen University & Research
Dr SM Kerstens, Royal HaskoningDHV, Amersfoort, the Netherlands
Prof. Dr P.P. Kalbar, Indian Institute of Technology Bombay, India
Dr M Ronteltap, Hoogheemraadschap van Delfland, Delft, the Netherlands

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Indra Firmansyah
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Table of contents

CHAPTER 1

General Introduction

1.1 The need for sustainable sanitation planning for resource recovery and reuse

The United Nations (UN) recognized the necessity to improve the access to clean water and proper sanitation as stipulated in Sustainable Development Goal 6 (SDG 6). SDG 6 aims to ensure availability and sustainable management of water and sanitation for all by 2030 (UN General Assembly, 2015). However, it is challenging to achieve the target as Unicef & WHO indicate that 4.2 billion people depend on unimproved sanitation services and 673 million people have no toilets at all and practise open defecation that leave human waste untreated, threatening human, environmental, public health, social and economic development (WHO, 2020). The implementation of adequate sanitation needs to quadruple if the world is to achieve the SDG sanitation targets (WHO, 2020). A failure to deliver SDG 6 can jeopardize the whole 2030 agenda if it is not well-planned and managed (Ho et al., 2020). The discharge of untreated human waste can lead to adverse health effects in individuals (Shuval, 2003), economic loss (Kerstens et al., 2016), increase the load of nutrients (nitrogen (N) and phosphorus (P)) and organic components to the environment. This is resulting in eutrophication that can decrease water transparency, cause the extinction of fish species, the death of coral reefs, the change structure of the zooplankton community and the emergence of toxic phytoplankton species (Pinto-Coelho et al., 2005, Howarth and Marino, 2006, Martinelli et al., 2006).

SDG 6 is also challenging in the context of the growing world population. It is predicted that the world population will reach 9.3 billion in 2050 and that 67% of the global population will live in urban areas (United Nation, 2012), which also increases the issues of food security; all people should have access to sufficient, safe, and nutritious food that meets their food preferences and dietary needs for an active and healthy life. However, the increasing food demand puts a pressure on food supply that requires fertilizers and water for crop production. These (conventional) fertilizers rely on high energy consumption and finite resources. Phosphorus (P) is in many places in the world a limiting nutrient for food production. At the same time reserves of P are estimated to be depleted in the next 50 to 400 years (Driver et al., 1999, Cordell et al., 2009, Sattari et al., 2012, Scholz et al., 2013, Reijnders, 2014). Nitrogen (N) fertilizer with the application of Haber-Bosch is relying on high energy use of between 1-2% of the global energy demand (Cherkasov et al., 2015), which is responsible for significant CO_2-eq. emissions (1-2%) (Smith et al., 2020). Meanwhile, water, essential for crop production is limited especially in arid and semi-arid regions. Recovering and re-using nutrients and water from waste and wastewater are therefore essential. However, urban systems are currently dominated by linear metabolism or throughput systems (Girardet, 2004).

The emerging concepts of urban circular metabolism or circular economy aim to replace linear resources management (Agudelo-Vera et al., 2012, Harder et al., 2019, Wielemaker, 2019), and offer an approach to exploit alternative resources, i.e. waste products through recovery and reuse. In this approach, domestic waste and wastewater are considered valuable resources containing organic matter, water, nutrients and other constituents that can be recovered and reused in agriculture (Blumenthal et al., 2000, Carr et al., 2004, Rijsberman, 2006). If these resources can be managed, recovered and reused in a sustainable way it may result in closing the nutrient cycle by recovering nutrients from sanitation systems and reusing these in agriculture. Doing so could even result in an abundance of food and economic growth (Kerstens, 2016). Therefore, the development of sanitation systems based on resource recovery can be an opportunity to improve the agricultural system in parallel.

1.2 Nutrient flows to understand urban nutrient metabolism

There is a requirement to assess the flow of goods and nutrients through urban area and their hinterlands in order to understand the so called ‘urban metabolism’. Urban metabolism is defined as “the sum total of the technical and socio-economic processes that occur in cities [and their hinterlands], resulting in growth, production of energy, and elimination of waste”(Kennedy et al., 2011, Broto et al., 2012). Most urban metabolism researches apply mass flow analysis (MFA) or substance flow analysis (SFA) at the city or country level to describe the flow of goods and substances that are resulting from technical and socio-economic process in cities (Færge et al., 2001, Schmid Neset et al., 2008, Mishima et al., 2010, Smit et al., 2010, Senthilkumar et al., 2012, Voskamp et al., 2015). The city and country levels offer opportunities for analysing interactions between different economic sectors and provide a clear link with public policies (Senthilkumar et al., 2012). MFA has been applied to quantify the resource flows, while SFA is an assessment of a particular material flow, such as nutrient or water. It is considered as an initial step to study dynamic processes in urban systems. However, the quantification of nutrient flows at a lower and smaller scale is limited.

A good understanding of the nutrient flows through urban systems and its hinterland is a key requirement for development and planning nutrient recovery and reuse. This requires data about the urban system, its hinterland and its sub-systems (Billen et al., 2012). However, one of the constraints to the quantification of nutrient flows is related to the difficulty of obtaining adequate data. A number of studies has applied SFA under uncertain or limited data situation (Huang et al., 2007, Montangero and Belevi, 2008, Do-Thu et al., 2011, Espinosa and Otterpohl, 2014). However, the limitation of these studies is that the agricultural system component is not or not well described, because it was not included in the system boundaries or because data was very difficult to obtain. Hence, an integrated analysis of nutrient flows between the urban sanitation and agriculture needs a more detailed study in order to support sustainable resource management (Firmansyah et al., 2017).

1.3 Performance of sanitation concepts with different sustainability indicators

A sanitation system/concept is a full train of technologies consisting of collection, transport, treatment/recovery and reuse options for domestic wastewater streams (Maurer et al., 2012). Conventionally collected domestic wastewater is a mixture of different waste streams with different composition and potential for resource recovery. The wastewater originates from diverse sources including the toilet, laundry, washbasin, bathroom, kitchen and is often combined with rainwater. Kujawa-Roeleveld and Zeeman (2006) reported the quantity of the different resources excreted daily by one person in the individual streams, viz. faeces, urine, grey water, and kitchen waste. Toilet wastewater, often referred to as black water, contains large amounts of organics and nutrients, but also pathogens, pharmaceutical residues, and hormones. The major part of N and P is present in the urine fraction of the black water.

A wide range of sanitation systems and wastewater technologies have been reviewed with their pros and cons for application (Eales et al., 2013, Nnaji, 2014, Tilley et al., 2014, Mehta et al., 2015). It can be categorized by the number of households served, distinguishing on-site systems (single household level), decentralized systems or community-based systems (typically 200-500 households) and off-site systems or centralised systems (Tilley et al., 2014, Egle et al., 2015). The systems can also be categorized based on the potential of resource recovery and reuse, viz. end of the pipe recovery of nutrients from centralized wastewater treatment plants (WWTP) and recovery from source separated streams (new sanitation system). In WWTP, nutrients from blackwater become diluted with other wastewater streams (if mixed with greywater), whereas new sanitation systems keep streams separate and concentrated (e.g., low flush toilet, separation of black and grey water or urine separation) to minimize contamination and dilution of streams facilitating nutrient and water recovery locally (Zeeman, 2012; Larsen et al., 2009). Harder et al. (2019) indicate that these systems can include low-tech and high-tech recovery technologies for application at community level.

The selection of sanitation concepts and their performance are important elements in the planning of sanitation systems for resource recovery and reuse in agriculture (Parkinson et al., 2014). The selection should be based on the performance in the context of sustainability following four domains of sustainability indicators, viz. environmental, technological, social-cultural and economic (Spiller, 2016). These indicators should be assessed for the full train of sanitation technologies, also including collection and transport, in order to optimise the resource recovery and reuse. Several efforts have been made to select sanitation technologies across different sustainability indicators. However, the assessments are mainly partial because of the complexities of the technological concepts. Some studies did not include the full train of technologies or did not cover all sustainability dimensions.

1.4 Sanitation planning development considering future development

A number of sanitation planning approaches exists, to assist decision makers and planners in selecting domestic waste and wastewater technological systems, such as frameworks, models, toolkits and software programs (Spuhler and Lüthi, 2020). Some approaches only focus on the treatment technologies, while others include collection and transport. Loetscher and Keller (2002) proposed several steps to screen and select feasible technologies based on a range of criteria, such as settlement characteristics, soil characteristics, quality of water supply, community profiles and pollution control measures. Larsen et al. (2010) discussed how to select alternative technologies by looking at the process engineering objectives. Kerstens et al. (2016) developed an approach to select the technology based on a limited number of indicators, such as population density and urban functions. Spuhler et al. (2020) developed a software tool (Santiago: SANitation sysTem Alternative GeneratOr) providing 41 sanitation technologies and 27 selection criteria to generate a set of sanitation systems. However, these studies do not provide a detailed assessment for the performance of different technologies along the four sustainability dimensions as proposed in this study, nor do these studies address the impact of future developments (such as climate change and demographic development) on the performance of these technologies.

Future developments and their potential impacts on sanitation systems can be studied with scenario techniques. Scenarios are qualitative descriptions of possible futures (ESPON, 2014) and are a specific category of future thinking (Dreborg, 2004, Carsjens, 2009). Börjeson et al. (2006) distinguish three categories of scenarios: predictive, explorative and normative, each sub-divided in two other types (Table 1.1).

Table 1.1 Typology of scenario categories (Börjeson et al., 2006)

Scenario type	**Quantitative/qualitative**	**Time-frame**
PREDICTIVE – What will happen?		
Forecasts	Typically quantitative, sometimes qualitative	Often short
What-if	Typically quantitative, sometimes qualitative	Often short
EXPLORATIVE – What can happen?		
External	Typically qualitative, quantitative possible	Often long
Internal	Qualitative and quantitative	Often long
NORMATIVE – How can a certain target be reached?		
Preserving	Typically quantitative	Often long
Transforming	Typically qualitative with quantitative elements	Often very long

External scenarios are tools to explore the uncertainties of the future by presenting several possible futures that can help planners to prepare for the future and support current decision making (Couclelis, 2005, Carsjens, 2009). External scenarios have been widely used in waste management research, especially in Life Cycle Assessments (LCA) related to waste management systems (Tascione and Raggi, 2012, Münster et al., 2013, Arushanyan et al., 2017). These studies explored the environmental performance of waste management systems under different external scenarios, including, for example, impacts on waste flows and energy use. However, research on the use of external scenarios for the selection of sanitation concepts is lacking. Kalbar et al. (2012, 2013) used scenarios to rank commonly used wastewater treatment technologies. However, these scenarios do not represent future external conditions, but the most common decision-making situations of wastewater treatment plants in India regarding the location of these plants (either in urban, suburban or rural area).

Most uncertainties addressed in urban metabolism studies are related to limited data availability and variability of data (Pahl-Wostl et al., 2007). However, there is also uncertainty about development trends that can affect the choice of a resource recovery and reuse system. These trends are for example related to climate change (van der Voorn et al., 2012), societal and economic change (van Vliet et al., 2010), that can influence the performance of a sanitation system. Therefore, these uncertainties need to be incorporated in the strategic planning of sustainable sanitation resource management. Such approach, using external scenarios, is currently lacking.

1.5 Products for reuse in agriculture

Waste(water) and its recovered resources can be reused in agriculture, as an alternative for chemical fertilizers and groundwater. In recent years, waste(water) products have been studied for their potential use in agriculture across the world. These products can be obtained from source-separated treatment systems or centralized wastewater treatment plants treating mixed municipal wastewater. An overview of waste(water) products that can be used as fertilizers can be seen in Table 1.2. These nutrient products originating from human waste(water) streams can substitute chemical fertilizers and thereby reduce the use of phosphate rock for P-fertilizer and reduce the use of fossil fuel to produce N-fertilizer (Mehta et al., 2015). The products can be used either for direct application as fertilizer on the field or as raw material in the fertilizer industry (Durrant et al., 1999).

Technologies to recover nutrients from waste(water) have been addressed in several review papers (Morse et al., 1998, Durrant et al., 1999, Le Corre et al., 2009, Li et al., 2009, Wang and Qiu, 2013, Mehta et al., 2015, Harder et al., 2019). However, little attention was paid on the impact of the use of recovered products on closing the nutrient cycle. Therefore, the impact needs to be assessed with more elaborations on fertilizer value and health risk of use of products with recovered nutrients in agriculture.

Table 1.2 Examples of recovered products from domestic waste and wastewater for reuse in agriculture (selected)

Origin streams	Type of products	References
Liquid-based products	Urine Aurin (Partially nitrified, concentrated urine)	(Jönsson et al., 2004), (Martin et al., 2020)
	Treated domestic wastewater Thermophilically anaerobically treated (high concentrated) BW effluent	(van Lier and Huibers, 2010, Etter et al., 2014) (Bisschops et al., 2019)
Solid-based products	Compost	(Vinnerås, 2007),
	Digested blackwater sludge	(Tervahauta et al., 2014)
	Sewage sludge ash (SSA)	(Adam et al., 2009)
	Struvite	(Le Corre et al., 2009, Cordell et al., 2011, Rahman et al., 2014)
	Algae grown on domestic wastewater streams	(Tuantet et al., 2013, Acién et al., 2017)
	Ammonium-sulphate/nitrate	(Bisschops et al., 2019)

1.6 Identified knowledge gap and research objectives

The previous sections show that the availability of technologies to recover resources from domestic waste and wastwater is large, but also that today's sanitation planning must account for this technological diversity, consider uncertainties and find a balance of ambitions around sustainable development and reuse of nutrients and water. From the investigation of work of previous scholars it appears that an approach and tool to identify the most appropriate technological system and its most suitable scale in a given local context is lacking. Likewise, there is little evidence that future uncertainty is accounted for in the planning of sanitation systems. Doing so however is important as the combination of selecting an appropriate technological system and accounting for uncertainty is expected to improve local resource management, reduce risks, provide robust and flexible strategies, and support decision making in urban-agricultural planning. The four main knowledge gaps identified in the previous sections, which are addressed in this thesis, are:

- Lack of investigations on nutrient flows of urban sanitation and agricultural systems at a smaller scale under limited data availability;
- Lack of investigations on the performance of sanitation concepts under four domains of sustainability indicators: environmental, technological, social-cultural, and economic;
- Lack of investigations on the performance of sanitation concepts under different future development;
- Lack of investigations on the effect of nutrient recovery and reuse in agriculture to realise a closed loop metabolism between city and hinterland.

Therefore, the aim of this thesis is to develop a planning approach to support recovery and reuse of nutrients, to couple sanitation-agricultural systems, while considering different future development scenarios.

The sub-objectives of the research are:

1. To develop a framework that facilitates a structured analysis of the link between sanitation and agricultural systems with regards to nutrient supply and demand;
2. To identify strategies for implementation of sanitation concepts in urban areas to recover nutrients from domestic waste(water) and reuse in agriculture;
3. To assess the effect of different future development scenarios on the performance and selection of sanitation concepts;
4. To assess the impact of agricultural reuse of nutrients for optimising nutrients recovery from domestic waste(water).

1.7 St. Eustatius as a case study

This thesis was embedded in the IPOP TripleP@Sea research project of Wageningen University & Research, theme "Biodiversity of the Dutch Caribbean". This TripleP@Sea theme focussed on collaboratively developing a conceptual framework for sustainable exploitation and an appropriate governance structure for tropical (small-island) ecosystem services, taking St. Eustatius as case study. St. Eustatius is one of the three islands in the Caribbean Netherlands with a special island status, a public body which is fully part of the Netherlands. St. Eustatius or locally known as Statia has a total area of 21 km^2 and a population of almost 4000 people (Figure 1.1). For centuries, St. Eustatius played a prominent role as a centre of trade and food production within the Caribbean region (Ayisi, 1992). In the 18^{th} century, the island was largely self-sufficient in terms of agricultural products (Government of Saint Eustatius, 2010). Currently, agriculture is a small sector in St. Eustatius and most of the agricultural products have to be imported (Schutjes, 2011). In addition, free roaming cattle on the island poses a risk for agricultural production. The government of St. Eustatius has identified this as problematic and is planning to improve agriculture practices on the island (Government of Saint Eustatius, 2010).

Several studies in the Caribbean region have indicated that the region is lacking adequate solid waste and wastewater infrastructure (Siung-Chang, 1997, Acurio et al., 1998). In St. Eustatius, the municipal solid waste is dumped at an open landfill, while the wastewater is discharged untreated or partially treated into soakage pits/cesspits (Government of Saint Eustatius, 2010). As a consequence, untreated waste(water) enters the coastal environment with detrimental effects for aquatic ecosystems. Eutrophication will lead to decreased water transparency, extinction of fish species, death of coral reefs, change structure of zooplankton and the emergence of toxic phytoplankton species (Pinto-Coelho et al., 2005, Howarth and Marino, 2006, Martinelli et al., 2006). In addition, the leaching of nutrients will threaten the quality of groundwater, particularly for a small island where there is no surface water available (Dillon, 1997).

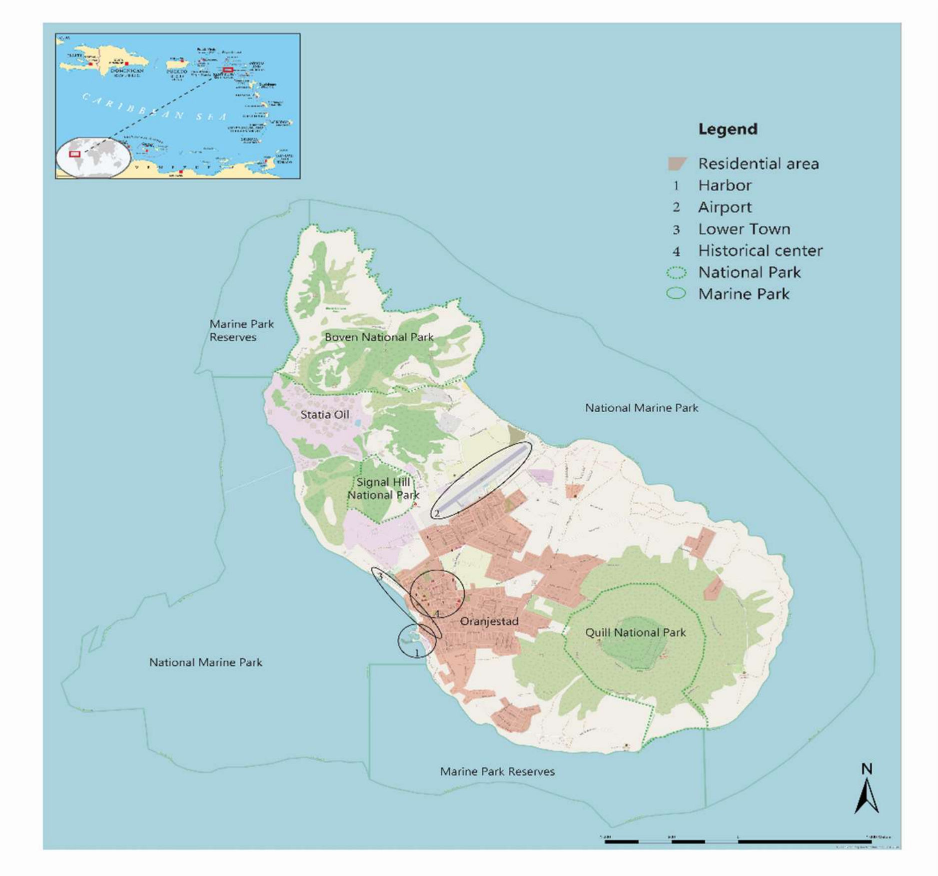

Figure 1.1 Map of St. Eustatius adapted from (Hoogenboezem-Lanslots et al., 2010)

The study at island-level (St. Eustatius) offers opportunities for analyzing interactions between urban (residential areas) and rural (agricultural activities) sectors in a terrestrial region. It is a relevant scale for identifying the key forces underlying nutrient use at present and opportunities for better nutrient resource management in the future. An island as case study also provides a clearly delineated area to assess the link between sanitation and agriculture focusing on nutrient recovery and reuse. Moreover, most small tropical islands are remote and therefore self-sufficiency of food production is an important theme for sustainable development.

1.8 Thesis Outline

This thesis presents the results of the research outlined above. It consists of six chapters: introduction, four research chapters that have been published in or will be submitted to international scientific journals, and a discussion chapter. Figure 1.2 shows the connection between chapters contributing to resource recovery and reuse as well as sustainability analysis.

Chapter 2 shows a baseline assessment of the current state of nutrient flows on the island. The assessment aims to provide an overview of N and P flows in a small island under limited data availability. The data availability is a limiting factor to assess the nutrient flows in agricultural and urban systems in a small island. The production of domestic waste(water) and consumption of nutrients of different agricultural products are mapped and quantified using substance flow analysis (Brunner and Rechberger, 2004, Niza et al., 2009). The output of this analysis is the mass balance of the current N and P flows in the island. The STAN software was used to visualise the flows and processes in the system (Cencic and Rechberger, 2008).

Chapter 3 provides an approach to evaluate the performance of sanitation concepts and the selection based on four different types of sustainability indicators: technological, environmental, economic and social-cultural. Three source-separated and two centralized sanitation concepts were compared based on the applicability of different technologies in the context of small tropical developing islands. The focus of this chapter is to evaluate the performance of sanitation concepts based on the current state of the development of St. Eustatius as a case study.

Chapter 4 provides an approach to assess the effect of future development on the selection of sanitation concepts. This chapter shows a stepwise approach to assess the performance of sanitation concepts under different sustainability indicators that are influenced by different future circumstances. The uncertainties of future development were identified based on Social, Economic, Environment, Political and Technological (SEEPT) factors. Four scenarios for St. Eustatius were developed to explore the future development of sanitation concepts, promoting nutrient recovery and reuse. The best performing sanitation system was selected.

Chapter 5 provides an assessment of the effect of the implementation of the selected sanitation concept in Chapter 4, including reuse of the products in agriculture, on the nutrient flows of a small tropical developing island. The focus of the chapter is to highlight the effect of the selection of a sanitation concept on the overall nutrient balance of a small tropical developing island using SFA model (STAN 2.5) descriptively and quantitatively.

Although St. Eustatius has been applied as a case study in this thesis, the operationalisation of the approach can be applied in other urban-rural areas. Chapter 6 discusses the application of the approach, highlighted in the chapters of the thesis, for other conditions. Moreover, the limitations of the approach are addressed in this chapter. Some practical recommendations for the context of St. Eustatius are also provided to support the applicability of sanitation concepts, promoting resource recovery and reuse and considering future developments.

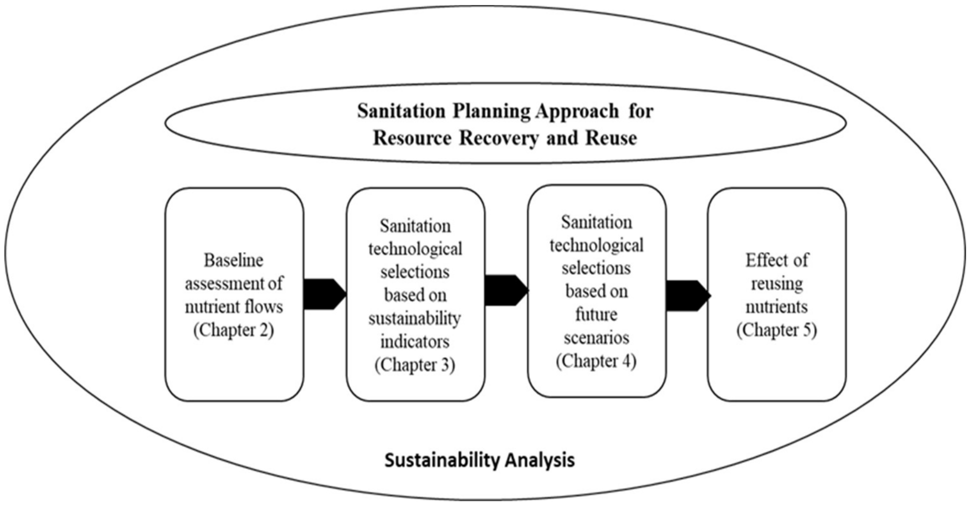

Figure 1.2 Overview of the connection between research chapters to develop a sanitation planning approach for resource recovery and reuse

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CHAPTER 2

Assessment of nitrogen and phosphorus flows in agricultural and urban systems in a small island under limited data availability

I. Firmansyah[a], M. Spiller[b], G.J. Carsjens[c], F.J. de Ruijter[d], G. Zeeman[a,e]

[a]Wageningen University & Research, Sub-department of Environmental Technology, Bornse Weilanden 9, 6708 WG, Wageningen, the Netherlands
[b]Research Group of Sustainable Energy, Air and Water Technology, Department of Bioscience Engineering, University of Antwerp, Groenenborgerlaan 171, 2020 Antwerpen, Belgium
[c]Wageningen University & Research, Landscape Architecture and Spatial Planning, P.O. Box 47, 6700 AA, Wageningen, the Netherlands
[d]Wageningen University & Research, Agrosystems Research, P.O. Box 616, 6700 AP, Wageningen, the Netherlands
[e]Leaf BV P.O. Box 500, 6700 AM, Wageningen, the Netherlands

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Abstract

Nitrogen (N) and phosphorus (P) are two essential macronutrients required in agricultural production. The major share of this production relies on chemical fertilizer that requires energy and relies on limited resources (P). Since these nutrients are lost to the environment, there is a need to shift from this linear urban metabolism to a circular metabolism in which N and P from domestic waste and wastewater are reused in agriculture. A first step to facilitate a transition to more circular urban N and P management is to understand the flows of these resources in a coupled urban-agricultural system. For the first time this paper presents a Substance Flow Analysis (SFA) approach for the assessment of the coupled agricultural and urban systems under limited data availability in a small island. The developed SFA approach is used to identify intervention points that can provide N and P stocks for agricultural production. The island of St. Eustatius, a small island in the Caribbean, was used as a case study. The model developed in this study consists of eight sub-systems: agricultural and natural lands, urban lands, crop production, animal production, market, household consumption, soakage pit and open-dump landfill. A total of 26 flows were identified and quantified for a period of one year (2013). The results showed that the agricultural system is a significant source for N and P loss because of erosion/run-off and leaching. Moreover, urban sanitation systems contribute to deterioration of the island's ecosystem through N and P losses from domestic waste and wastewater by leaching and atmospheric emission. Proposed interventions are the treatment of black water and grey water for the recovery of N and P. In conclusion, this study allows for identification of potential N and P losses and proposes mitigation measures to improve nutrient management in a small island context.

Key words: substance flow analysis (SFA), Nitrogen, Phosphorus, small island system, urban-agriculture, urban metabolism.

2.1 Introduction

Cities are centres of resource consumption and waste production. Urban systems have been compared to organisms or ecosystems that have a metabolism. Kennedy et al (2007) defined this urban metabolism as the technical and socio-economic processes that occur in cities, resulting in growth, production of energy and waste. It has been suggested that this metabolism of cities is mainly linear or throughput oriented, but should be changed to a more circular approach in which resources are used efficiently and reused as much as possible (Girardet, 2004, Agudelo-Vera et al., 2012). In particular, the reuse of nutrients such as N and P from urban areas has been suggested as an option that makes it possible to reduce environmental pressures from nutrient losses. Reuse of these nutrients is crucial because the fossil fuel based energy used for production of N-fertilizer via the Haber-Bosch process is approximately 37-45 kJ/gN (Maurer et al., 2003). The global energy requirement for this process is equal to about 1% of the world's total annual energy supply (Smith, 2002). P-fertilizer is obtained from mining phosphate rock, which is a finite and non-renewable resource that is estimated to be depleted in the next 50 to 400 years (Cordell et al., 2009, Sattari et al., 2012, Scholz et al., 2013, Reijnders, 2014).

Cities rely on their hinterlands for food production. The word hinterland is originating from German and literally means the "land behind" and is defined as the region, economically tied to an urban area (Baccini and Brunner, 2012). In the present globalised economy, this urban hinterland is extended to the entire globe. Therefore, it is hard to progress towards a so-called circular or reuse oriented city system where resources, such as the non-renewable P, can be continuously recycled. For example, cities rely on imported food for human consumption, and fertilizers containing N and P for agricultural production (e.g. P is mainly sourced in Morocco and China) (Ma et al., 2010; van Dijk et al., 2016). By recycling these resources locally from domestic waste and wastewater and reusing them in nearby agricultural production, the potential loss of N and P can be reduced and the production and mining of nutrients reduced. Progressing towards this circular system is further challenging, because of the large number of agents involved in this system change; these actors include: food supplier, waste producer, and farmers at the local scale (Fernandez-Mena et al., 2016).

The problems that cities face are even more amplified on small islands (Deschenes and Chertow, 2004). They represent physically constrained systems with unique challenges that are characterized by small size, insularity, remoteness, proneness to natural disasters, social isolation, and external dependency (Briguglio, 1995, Méheux et al., 2007, Saint Ville et al., 2015). Because of limited resource availability, most resources in small islands have to be imported for a large part of their domestic needs (Krausmann et al., 2014). Furthermore, the terrestrial ecosystems have a limited buffering capacity as there are few or no surface water systems to attenuate pollution with N and P, before entering the marine ecosystem. In the marine ecosystems, elevated N and P concentrations cause eutrophication. This can lead to decreased water transparency, extinction of fish species, death of coral reefs, change of the zooplankton community and the emergence of toxic phytoplankton species (Pinto-Coelho and Bezerra-Neto, 2005, Howarth and Marino, 2006, Martinelli et al., 2006). In addition, the leaching of nutrients will threaten the quality of the small island's groundwater lenses (Dillon, 1997). This makes small islands highly vulnerable to both global economic change and domestic environmental degradation. Hence, the concept of reusing N and P to protect the marine ecosystem and to achieve self-sufficiency in food production is especially appealing to small islands (Douglas, 2006, Forster et al., 2011).

A key requirement for development and planning of reuse is a good understanding of the resource flows through urban systems and their hinterlands. This requires data about the urban system, its hinterland and its sub-systems (Billen et al., 2012). Billen et al. (2012) investigated the issue of closing nutrient cycles in different cities and indicated the necessity to connect urban and hinterland systems. However, the data for closing the nutrient cycles is often not readily available, in particular when investigating the interlinkages between cities and their hinterland. Montangero et al (2007) indicated that one of the constraints to the quantification of N and P flows is related to the difficulty of obtaining adequate data. A number of studies, therefore, aim to provide methods to conduct material or substance flow analysis under uncertain or limited data situation (Huang et al., 2007, Montangero and Belevi, 2008, Do-Thu et al., 2011, Espinosa and Otterpohl, 2014). In these studies, the methodology of Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) has been adapted to assess urban water management in Kun Ming City, China (Huang et al., 2007), to optimise nutrient management in environmental sanitation systems in the urban context of Hanoi City, Vietnam (Montangero and Belevi, 2008), to assess nutrient management in the rural area of Hoang Tay and Nhat Tan communities, Vietnam (Do-Thu et al., 2011), and to assess urban water and wastewater management system in the city of Tepic, Mexico (Espinosa and Otterpohl, 2014). The methodology applied in these studies relies on the maximum use of incomplete local data, and the use of data retrieved from literature or expert judgement. However, the limitation of these studies is that the agricultural system component is not or not well described, because it was not included in the system boundaries or because data was very difficult to obtain.

SFAs have been used to quantify the loss of N and P flows at different spatial scales, but have not been applied to small islands to couple urban-agricultural systems. For example, the flows of N and P related to agricultural systems have been studied at global (Liu et al., 2008, Bouwman et al., 2009), national (Antikainen et al., 2005, Chen et al., 2008, Smit et al., 2010, Ott and Rechberger, 2012, Senthilkumar et al., 2012, Cooper and Carliell-Marquet, 2013, Smit et al., 2015), or city level (Schmid Neset et al., 2008, Li et al., 2011, Wu et al., 2014). Moreover, the SFA and MFA methods have been applied to study N and P flows related to sanitation systems in urban areas of developed countries (Belevi, 2002, Sokka et al., 2004, Meinzinger et al., 2007) and developing countries (Huang et al., 2007, Meinzinger et al., 2009).
The objective of this study is to develop an SFA approach for the assessment of coupled agricultural and urban systems under limited data availability in a small island. The island of St. Eustatius in the Caribbean was used as a case study. The developed approach aims to provide useful information for policy makers to improve nutrient (N and P) management by identifying the source of the nutrient losses and stocks that are potentially available for agricultural production.

2.2 Methodology

2.2.1 Description of the study area

St. Eustatius is a small tropical island in the Caribbean and is since 10th October 2010 officially a special municipality of the Netherlands. Formerly, St. Eustatius was part of the Netherland Antilles, which was a constituent country of the kingdom of the Netherlands. The island has a total area of 21 km2 and a population of 3897 people in 2013 (CBS, 2014). Geologically, the island has mountain-like areas in the south and north (Figure 2.1). The south is characterized by the 600 meter-high dormant volcano Quill, and the smaller pair Signal Hill/Little Mountain and Boven Mountain to the northwest. These areas are mostly covered by natural vegetation. Urbanisation on the island is located mostly in the western part of the island. Urban dwellings are scattered in a largely green area in the eastern part (Hoogenboezem-Lanslots et al., 2010).

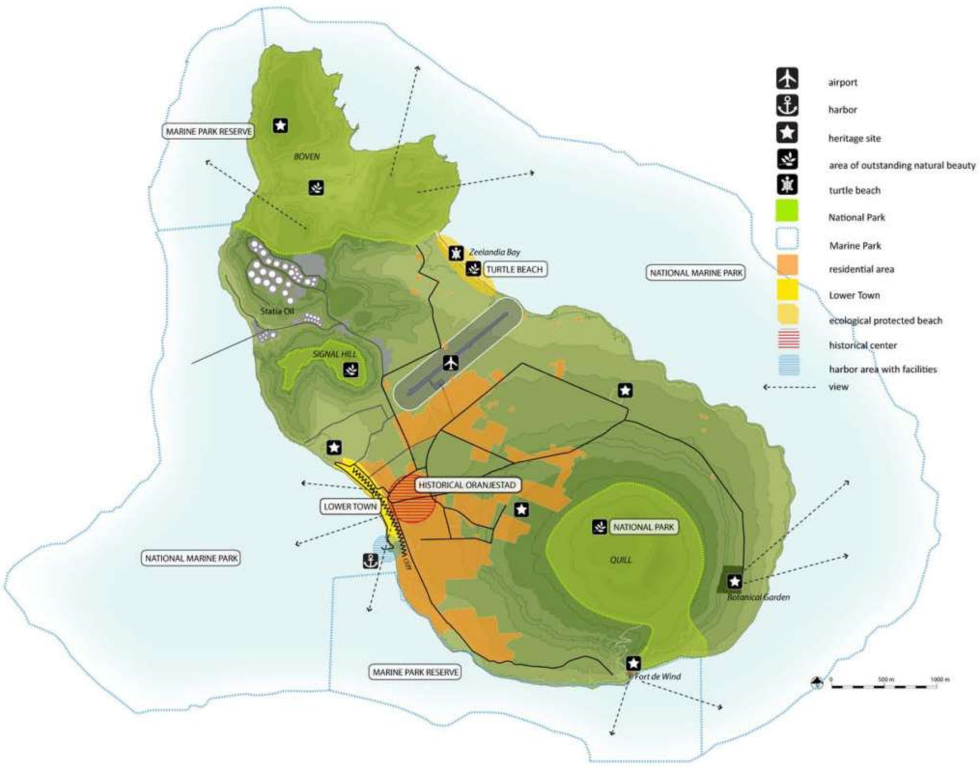

Figure 2.1 Map of St. Eustatius (Hoogenboezem-Lanslots et al., 2010)

Agricultural activities on the island consist of livestock and horticulture production. Most animal products from St. Eustatius are consumed locally or exported to the neighbouring islands, while crop products are locally distributed. Since the agricultural sector of St. Eustatius is limited, the food system of St. Eustatius is dominated by import; only 6% of the consumed food is of local origin. However, St Eustatius has potential for development, as historically it has played a prominent role in agricultural production in the region (Ayisi, 1992; Schutjes, 2011). Currently, St. Eustatius has 143.7 ha of agricultural land (6.8% of the total area), consisting of 3.6 ha arable land (horticulture) and 140.1 ha pastures (Smith et al., 2013).

The solid waste generated on the island is collected and dumped in an open landfill. Cistern flush toilets with soakage pits are the most common on-site wastewater systems in St. Eustatius. Most of the pits on the island only receive black water, which is the mixture of urine, faeces, and flushing water. The liquid fraction from the pits infiltrates to the groundwater, while the sludge remains in the pit. Grey water, which is generated in the kitchen and from washing activities, such as doing the laundry, dishwashing and other kitchen activities, showering and bathing, is discharged to the open ground.

2.2.2 Research approach

The method used in this study is Substance Flow Analysis (SFA) (Bringezu et al., 2009). The core principle of SFA is the mass balance principle, derived from the law of mass conservation (Van der Voet, 2002). It is used to determine the magnitude and location of losses and stock changes of substances in the system (Bringezu and Moriguchi, 2002, de Haes and Heijungs, 2009).

The system boundary applied in this study is the geographical land border of St. Eustatius (terrestrial region). Fieldwork was conducted in 2014 to collect background information on domestic waste and wastewater management, agricultural systems, and environmental conditions in the study area. During this fieldwork, it became apparent that the quality and quantity of the data available at St. Eustatius were not suitable to carry out a comprehensive SFA. Table 2.1 shows all the data that was collected during interviews, retrieved from government reports and from online databases. The 11 interviews that were carried out covered nearly all the officials from the municipality, private companies, and non-governmental organisations (NGOs) on the island. In particular during the interviews with the three farmers, it became clear that the quality of the data was poor, due to the lack of official records, billing or other management information, which are typical for EU farming businesses.

Table 2.1 List of available data collected during fieldwork in 2014 and from secondary data sources

Description of data and data source	Unit	Value
Population (CBS, 2014)	Inhabitants	3897
Additional number of visitors[a]	Persons	196
Total Land (Smith et al., 2013)[b]	ha	2109
Agricultural land		
Arable land (horticulture)	ha	3.6
Pastures	ha	140.1
Natural land		
Rangeland	ha	768
Forest	ha	866
Bare/sparsely vegetated	ha	151
Urban land	ha	181
Livestock (Debrot et al., 2015)		
Beef cattle	cows	1012±468
Goats	goats	2470±807
Sheep	sheep	1300±992
Food consumption in Netherland Antilles (FAOSTAT, 2014)		
Total food protein	g/cap per day	93.2
Total animal protein	g/cap per day	58.4
Total vegetable protein	g/cap per day	34.7
Local vegetable production (Hazel, 2014)		
Tomatoes	kg/year	7650
Cucumber	kg/year	8765
Lettuce	kg/year	3265
Water Melon	kg/year	3360
Spinach	kg/year	406
Pineapple	kg/year	1600
Pumpkins	kg/year	4425
Exported Animal products (LVV, 2014)		
Cows meat (carcass)	kg/year	18583
Goat meat (carcass)	kg/year	328
Sheep meat (carcass)	kg/year	1126
Imported fertilizer (Hazel, 2014)		

NPK fertilizer (13-13-13)	ton/year	1
Municipal waste production (DEI, 2014)		
Household organic waste (kitchen waste)	kg/cap per year	39.3
Market waste (restaurants, supermarkets)	kg/cap per year	35.4
[a] The number of visitors was estimated based on 10,250 tourists visiting the island per year (Tieskens et al., 2014) and an assumed average stay of 7 days. [b] Analysis of satellite images results in unclassified areas because of cloud cover (219 ha). The area was allocated for 1/3 to natural land–rangeland, 1/3 to natural land–forest and 1/3 to urban and industrial land, based on the map of St. Eustatius.		

In this study, eight sub-systems were defined with stocks, input and output flows. These sub-systems are agricultural and natural lands, urban lands, crop production, animal production, market, household consumption, soakage pit, and open-dump landfill (Figure 2.2). Twenty-six flows associated with the movement of materials containing N and P through the sub-systems and its quantification methods were identified (Figure 2.2; detail for calculation in the supplementary material (SM) Table S1.1). The year of 2013 was selected as a reference year. The STAN version 2.5 software (Cencic and Rechberger, 2008) was used for consideration of uncertainties, data reconciliation, and visualisation.

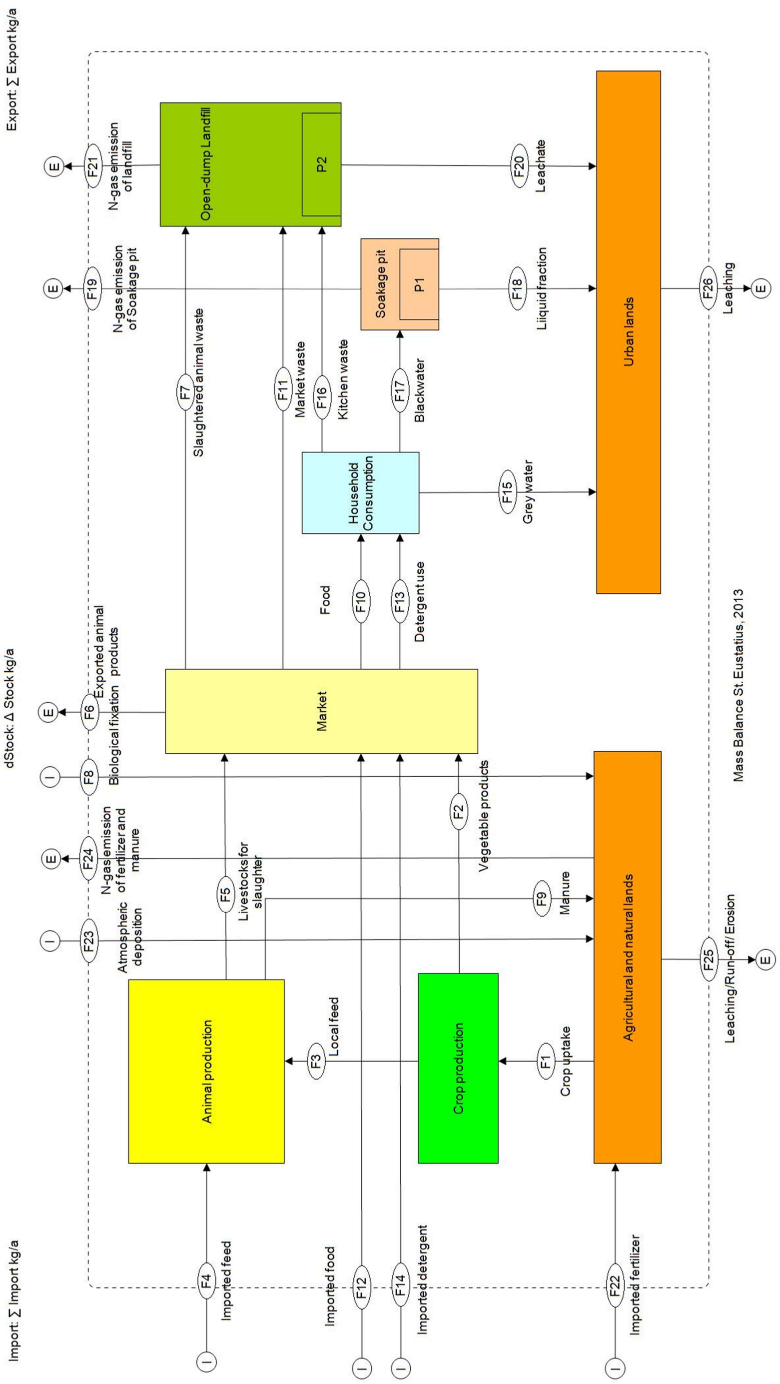

Figure 2.2 Schematic representation of analysed system using STAN 2.5 (Cencic and Rechberger, 2008); baseline study in St. Eustatius

2.2.3 Data sources and quantification per sub-system

2.2.3.1 Crop Production

The sub-system of crop production includes arable land (horticulture) for vegetable products for local food and pastures for local animal feed. The food products represent a flow to the market sub-system, while the feed products are flows to the animal production sub-system. The crop production sub-system receives input flows of N and P from crop uptake (F1). Crop uptake (F1) is defined as the total amount of N and P in products that leave the agricultural and natural lands. Crop residues that remain on the field are regarded as an internal flow and are not studied separately. N and P in vegetable products (F2) are estimated based on the nutrient content of the products. N and P in local animal feed (F3) are estimated from the total nutrient requirement of livestock in St. Eustatius. The nutrient requirements were calculated as the requirements for maintenance and growth. The nutrient requirements for maintenance per beef cattle were based on NRC (2000), and for maintenance per goats and sheep were based on NRC (2007). These nutrient requirements were adjusted using factor 0.6 for beef cattle, 0.8 for goats and 1 for sheep to correct for a lower weight of animals at St. Eustatius (FAO, 2015). The nutrient requirement for growth is assumed equal to the content in slaughtered animals based on the assumption of no changes in the total amount of animals on the island.

2.2.3.2 Animal production

The sub-system animal production comprises of N and P flows associated with the production of livestock, feed consumption, and the generation of manure. Livestock receives nutrients through feed consumption and most of the nutrients leave the animal body through manure excretion. In St. Eustatius, most livestock is roaming freely on the island, while only a small number of livestock are kept in a stable or a fenced area (Debrot et al., 2015). The roaming animals receive the nutrients from local feed uptake, while the fenced animals receive the nutrients from both local and imported feed. Within this sub-system, N and P flows are explicitly shown in the flows of imported feed (F4), locally produced feed (F3), manure (F9), and livestock for slaughter (F5). According to the mass balance principle, manure (F9) is calculated as the inputs of local and imported feed minus the output of livestock for slaughter. N-gas emission from manure and fertilizer (F24) in this sub-system is calculated based on the assumptions of Sutton et al. (2013). To estimate the nutrient flow of imported feed (F4) and locally produced feed (F3) total nutrient requirement for livestock was calculated. It is assumed that 80% of all livestock consumed local feed because of the high ratio of roaming animals, while the remaining 20% livestock consumed feed with a ratio between local and imported feed of 50:50. Following the standard of Tropical Livestock Units (TLUs) (FAO, 2015), the average weight of cattle is 250 kg, and goats and sheep are 30 kg each. The nutrient content per live weight is assumed for beef cattle (27 g N/kg, 7.4 g P/kg), goat (24 g N/kg, 7.9 g P/kg), and sheep (25 g N/kg, 7.8 g P/kg) (Bruggen, 2007).

2.2.3.3 Market

All products needed for domestic consumption are distributed to the household through the market sub-system, while some animal products are exported outside the system. The flows containing N and P include the processing and trade of local and imported food, imported detergent and the use of the detergent by households. The market sub-system consists of the flows of vegetable products (F2), livestock for slaughter (F5), exported animal products (F6), slaughtered animal waste (F7), imported food (F12), imported detergent (F14), food (F10), detergent use (F13) and market waste from supermarkets and restaurants (F11). The N and P content in the vegetable products transferred to market sub-system was estimated based on The Souchi Fachman Kraut (SFK) online database (Souchi, 2001). SFK online database provides the composition of various food items with different constituents including detailed information on nutrition contents.

The imported food flow represents food products of both plant and animal origin that are transported to St. Eustatius. Due to lack of detailed information on the types of imported products, the N and P contained in the imported food (F12) are estimated based on the difference between the total supply of local food products (animal and crop products) and the sum of food consumed by local people and market waste (see section 2.3.4). Livestock (F5) is estimated based on the annual number of animals slaughtered for local consumption and export activities. Landbouw, Veeteelt en Visserij (LVV), a local governmental agency focusing on the development of agriculture and fisheries, provided data on the number of animals locally slaughtered, and the amount of exported products in carcass weight (LVV, 2014). About 4 beef cattle, 20 goats and 10 sheep are slaughtered monthly for local consumption. N and P in slaughtered animal waste (F7) is calculated based on the difference between the nutrient content of live animals and animal products. The animal products consist of locally consumed (only meat fraction) and exported products (meat with bones). The fraction from live animal to carcass and carcass to meat was derived from Smit et al. (2015).

2.2.3.4 Household consumption

The N and P flows to the household consumption sub-system are calculated based on the total food consumed by local people and tourists. It is assumed that tourists' food consumption is similar to local food consumption. This consumption takes place in households, restaurants and offices. Food consumed by households is partly excreted as blackwater (faeces and urine) and partly disposed of as kitchen waste. The N and P contained in the food flow (F10) are calculated based on FAO country specific food supply information. The average total food protein supply of the Netherland Antilles is 93.2 g/cap per day in 2010 (FAOSTAT, 2014). The N and P contained in food supply are calculated based on the formula determined by Vinnerås and Jönsson (2002) using the FAO country specific food supply information and the fact that plant food protein contains on average twice as much P per gram as compared to animal protein (Vinnerås and Jönsson, 2002, Jönsson et al., 2004).

The use of detergent (F13) for laundry and dishwashing contributes to the P losses through the discharge of greywater (F15). These flows represent the amount of imported detergent to St. Eustatius (F14). It is assumed that the detergents do not contain N. P emission of laundry detergent and dishwasher detergent is estimated using information of Van Drecht et al. (2009) (see SM table S1.1), amounting to 0.62 kg P/cap per year.

2.2.3.5 Soakage pit

The soakage pits described in this study only receive blackwater (faeces, urine and flush water). The toilets in St. Eustatius are generally constructed with a single pit, where the liquid fraction of the blackwater infiltrates into the ground through the bottom, and the solids accumulate in the pit as faecal sludge. Transfer coefficients for N to faecal sludge in pit latrines are estimated to range from 9 to 27%, with the remaining N going to leachate (Montangero and Belevi, 2007). Similarly, of the total P input flow to the soakage pit (F17), 18-40% remains in faecal sludge, and the remaining 60-82% is leached (Montangero and Belevi, 2007). Another study indicated that 2-20% of total N and <1% of total P are lost to groundwater from pit latrines (Nyenje et al., 2013). This low percentage of leaching is due to the type of soil and the type of ventilated pit latrine system applied, where some of the N is emitted to the atmosphere. Within the present study, nitrogenous gas emission from the soakage pit (F19) is not considered because the pit is located underground, preventing ammonia emission. Moreover, nitrification will be limited as mainly anaerobic conditions prevail in the pit. In St. Eustatius, soils are generally well draining. Therefore, the amount of N and P transferred to urban land is estimated based on the transfer coefficients for leachate from Montangero and Belevi (2007). As there is an accumulation of N and P in the pit, a stock change (P1) is taken into account in the sub-system.

2.2.3.6 Open-dump landfill

Within this study, the flows of slaughtered animal waste (F7), kitchen waste (F16) and market waste (F11) are considered as input flows to the open-dump landfill sub-system. Output flows include leachate (F20) and nitrogenous gas emission (F21). A stock (P2) is included in this sub-system to represent the amount of N and P accumulating in the landfill. To estimate N and P content in input flows of supermarket waste (F11) and kitchen waste (F16), a percentage of dry matter of 40% is assumed (Eggleston et al., 2006), and N and P concentrations in the dry matter of 3.16% and 0.52% respectively (Zhang et al., 2007).

The quantity of N lost from waste is associated with the volume of water that percolates through the landfill. N is lost from the open-dump landfill sub-system through leachate and nitrogenous gas emission. Landfill leachate is mainly generated due to rain water percolating through the waste (Mahmud et al., 2012). Factors affecting the amount of N that is leached are related to the age of landfill, the climate that influences precipitation and evaporation, seasonal weather variation, waste type and composition, water content and the degree of compaction of the waste (Renou et al., 2008). Due to lack of data on the leachate concentration and volume of gas generation from landfill in St. Eustatius, transfer coefficient of total N from landfill to leaching is estimated to range from 21 to 27% (Wang et al., 2014), and to gas emission from 16 to 25% (Onay and Pohland, 1998). Because P movement is not linked to water percolation, but rather to movement of sediments, leaching is not taken into account for P (Kjeldsen et al., 2002). Erosion is not taken into account as the waste fraction remains on the open-dump landfill sub-system. As there is no P emission to the atmosphere, 100% of P accumulates in the landfill.

2.2.3.7 Agricultural and natural lands

The agricultural and natural land sub-system is a nexus for many N and P flows. Some of the flows are already described in previous sections except for imported fertilizer (F22), atmospheric deposition (F23), biological nitrogen fixation (F8), nitrogenous gas emission from fertilizer and manure (F24) and leaching/erosion/run-off (F25). Within this sub-system, it is assumed that P can accumulate in the soil, while there is no N accumulation in the soil (Sutton, 2013). The absence of N accumulation in the agricultural and natural land sub-system is based on a steady state approach by assuming no change in soil organic matter content (Van Drecht et al., 2003).

There are no official records of chemical fertilizer use in St. Eustatius. Therefore, data on the amount of imported fertilizer is retrieved from a local farmer (Hazel, 2014). The application rate of fertilizer is assumed to be the same for the other farmers and applied on the total arable land. Based on Cleveland (1999), the amount of symbiotic and non-symbiotic biological N fixation is estimated as 2.7 kg N/ha for grassland and an average of 23 kg N/ha for forest and shrub land (Cleveland et al., 1999). For terrestrial regions in remote areas, N deposition is estimated about 0.5–1 kg N/ha per year (Galloway et al., 2004). Annual P deposition on the island of St. Eustatius is estimated to be 0.05 kg P/ha, based on simulation of long-range atmospheric P transport by Mahowald et al., (2008, cited by Tipping et al., 2014).

In the agricultural and natural sub-system, total N loss was calculated based on the N surplus. N is lost from the agricultural and natural sub-system through ammonia volatilization, soil denitrification, and leaching and runoff (Cameron et al., 2013). For the present study, global estimates reported by Sutton et al (2013) were used to estimate the division of N loss over these routes: 24% is lost as ammonia, 16% by soil denitrification and 60% by leaching and runoff. P losses through erosion and runoff were estimated based on measured export of P from Caribbean tropical rainforest catchments in Dominica, St Lucia, and St. Vincent (McDowell et al., 1995). Export of P from different catchments varied between 0.03 and 0.48 kg P/ha per year, with an average of 0.134 kg P/ha per year. Average annual rainfall on the three islands is 2083, 2301 and 1583 mm/year respectively (FAO, 2016), which is about twice the amount of rainfall on St. Eustatius in 2013 (SEAWF, 2016). Based on these differences in rainfall, export of P by erosion and runoff from St. Eustatius was estimated at half the average amount measured by McDowell et al. (1995).

2.2.3.8 Urban land

Urban land sub-system includes the land or soil that receives N and P discharged from the household sub-system in the form of grey water (F15), leachate from the open-dump landfill sub-system (F20) and the liquid fraction from the soakage pit sub-system (F18). N leaches and infiltrates into ground water (F26) and leaves the system boundary, while P accumulates in the soil as net stock.

2.2.4 Uncertainty analysis

The methods applied to quantify N and P flows in this study are various and characterized by different levels of uncertainty. The uncertainty analysis applied in this study using the concept introduced by Hedbrant and Sörme (2001), to estimate uncertainties of N and P flows. The concept is based on the categorisation of data sources. The data sources were categorised based on the availability of the data ranging from national to local data, published or unpublished data, and these data were ranked based on the estimated reliability. Each data set was assigned an uncertainty level corresponding to an interval established by an uncertainty factor, corresponding to the representativeness and accuracy of the data source and resulting in an estimated uncertainty range. Since the method of Hedbrant and Sorme (2001) produced asymmetrical intervals as uncertainty, the method of Laner et al. (2015) was applied to modify the asymmetrical interval into symmetric interval for use with the STAN software. In this adaptation, the uncertainty factors are converted into coefficients of variation (CV) (Table S1.2). Laner et al. (2015) define the CV as the mean value plus two standard deviations, with a symmetric interval around the mean corresponding to a 95% confidence interval.

Table 2.2 Uncertainty level with corresponding uncertainty factors and coefficient Variance (CV) applied for different data sources

Level	Uncertainty factor	Coefficient Variance (CV)	Information source	Example
1	1.11	±10%	Official national/local statistics, published paper/report related to St. Eustatius or in the region of Caribbean	Food consumption data
2	1.33	±25%	Unpublished reports, published paper/report from global study	Animal production data
3	2	±50%	Experts estimation	Imported fertilizer, agricultural production

Level 3 was assigned to the data retrieved through interviews, such as data of imported fertilizer and agricultural production, as these interviews generally yielded data from memory. Level 2 was assigned to the data retrieved from unpublished reports provided by local authorities, such as animal production data. This data range was chosen as these reports have not been approved or validated. The least uncertain information sources are official statistics and published papers or reports. Level 1 was assigned to these data sources. For the generally accepted knowledge (e.g. molar mass), there is no uncertainty level assigned to this type of data.

The software STAN was used for modelling substance flows and for data reconciliation including the uncertainty analysis (Cencic and Rechberger, 2008). In STAN, all uncertain data and parameters are described by normally distributed independent random variables. Uncertain quantities are expressed by the mean and a measure of variance based on the standard deviation. Furthermore, STAN uses Gaussian error propagation and data reconciliation to calculate the uncertainty of model outputs if there is a conflicting uncertain data. The analysis in STAN will balance the results based on the uncertainty associated with each flow (see SM Table S1.2 and Table S1.3).

2.3 Results

2.3.1 Overall balance

St. Eustatius receives a total input flow of 65,304 ± 8% kg N/year and 3861 ± 11% kg P/year, with a total output flow of 59,890 ± 10% kg N/year and 356 ± 20% kg P/year (Figure 2.3 and 2.4). Therefore, a net stock change of 5414 ± 67% for N and 3505 ± 12% for P takes place annually. The natural input flows to the system are associated with the N-biological fixation (41,430 ± 12% kg N/year) and atmospheric deposition (1591 ± 27% kg N/year and 105 ± 25% kg P/year). The main anthropogenic N and P inputs to the system are via imported food: 30% of the total N inflow (19,712 ± 13% kg N/year) and 61% of total P inflow (2381 ± 19% kg P/year). Imported feed, fertilizer, and detergent containing N and P represent about 4% of N and 36% of P of the total input flows.

The amount of N that is lost from the system comprises of leaching/run-off of agricultural and natural lands (44% of N; 26,460 ± 24% kg N/year), leaching from urban lands (24% of N; 14,266 ± 18% kg N/year), N-gas emission from fertilizer and manure (29% of N; 17,637 ± 15% kg N/year), exported animal products (1% of N; 595 ± 29% kg N/year), and N-gas emission from landfill (2% of N; 932 ± 29% kg N/year). P leaves the island mainly through exported animal products (6% of imported P; 215 ± 28% kg P/year); the P loss from erosion/ runoff from agricultural and natural lands is relatively small (141 kg P/year) as the P content of the eroded soil is low. Most P accumulates in the land systems soakage pit and landfill. This P is currently inaccessible for reuse in agriculture.

2.3.2 Balance per sub-system

The total crop uptake in the crop production sub-system is 21,123 ± 13% kg N/year and 4217 ± 14% kg P/year. Of this total flow, local animal feed contains 21,077 ± 13% kg N/year and 4210 ± 14% kg P/year that are transferred to the animal production sub-system, and local vegetables contains 46 ± 54% kgN/year and 7 ±

54% kg P/year that are transferred to the market sub-system. Similar to local vegetables, livestock for slaughter (1449 ± 26% kg N/year and 413 ± 26% kg P/year) are transferred from the animal production sub-system to the market sub-system. These local animal and vegetable products represent 8% of N and 19% of P consumed by local people and tourists in the household consumption sub-system, in which total food consumption is accounted for 18,101 ± 14% kgN/year and 2,102 ± 14% kg P/year.

The N and P entering the household consumption sub-system are transferred to blackwater (16,068 ± 16% kg N/year and 1767 ± 24% kg P/year), greywater (783 ± 27% kg P/year), and are disposed of as kitchen waste (2033 ± 27% kg N/year and 335 ± 27% kg P/year) to the landfill. All of the calculated P content in greywater originates from the detergent. About 11% of N and 16% of P in total food consumption by households is disposed of as kitchen waste. Blackwater contains 77% of N and 72% of the P consumed. Of the total N and P in blackwater, 80% of N (13,175 ± 19% kg N/year) and 71% of P (1255 ± 24% kg P/year) are leaching from the soakage pit and enter the soil system. N is then washed out to the ground water, while the PO_4^{3-} ions are partly adsorbed to soil minerals, and partly leached due to high water use for flushing toilets (about 10 l per flush) in St. Eustatius. The remaining 20% of N (2893 ± 125% kg N/year) and 29% of P (512 ± 102% kg P/year) are retained in the soakage pit as sludge.

The main N and P input to the open-dump landfill sub-system are kitchen waste (2033 ± 27% kg N/year and 335 ± 27% kg P/year), market waste (1826 ± 27% kg N/year and 301 ± 27% kg P/year), and slaughtered animal waste (685 ± 34% kg N/year and 183 ± 35% kg P/year). Of the total input to the landfill, about 21% of N (932 ± 29% kg N/year) is lost to the atmosphere, nearly 24% of N (1091 ± 14% kgN/year) leaches, and nearly 55% of N (2893 ± 125% kg N/year) accumulates in the landfill. In following years, the organic matter containing this N might be degraded, releasing N to the atmosphere or ground water. All P entering the open-dump landfill accumulates (819 ± 17% kg P/year). Some P remains in the landfill in the pile of waste, like part of the P in slaughter waste such as bones, which is not susceptible to leaching. Another fraction of waste in the landfill is easily degradable, and the nutrients can leach into the soil under the landfill, where it is assumed to be retained as a result of the P sorption capacity of the soil (Sharma et al., 2015).

Most N and P from the animal production sub-system are transferred to the agricultural and natural lands sub-system as manure (21,809 ± 13% kg N/year and 4219 ± 14% kg P/year). N and P uptake by local crops (21,123 ± 25% kg N/year and 4217 ± 14% kg P/year) are a bit smaller than the input with manure. The agricultural and natural land sub-system has a net P stock change of 136 ± 115% kg P/year. N loss from the agricultural and natural land sub-system is through N-gas emission, leaching, and erosion/run-off. About 40% of N loss is emitted to the atmosphere due to ammonia volatilization, N_2 and N_2O emission, which accounted for 17,637 ± 15% kg N/year. Additionally, about 60% of N is lost through leaching and erosion/run-off, which accounted for 26,460 ± 19%. In the urban land sub-system, P accumulation accounts for 2038 ± 18% kg P/year. For the case of N, a total of 14,266 ± 18% kg N/year leaches from urban land sub-system.

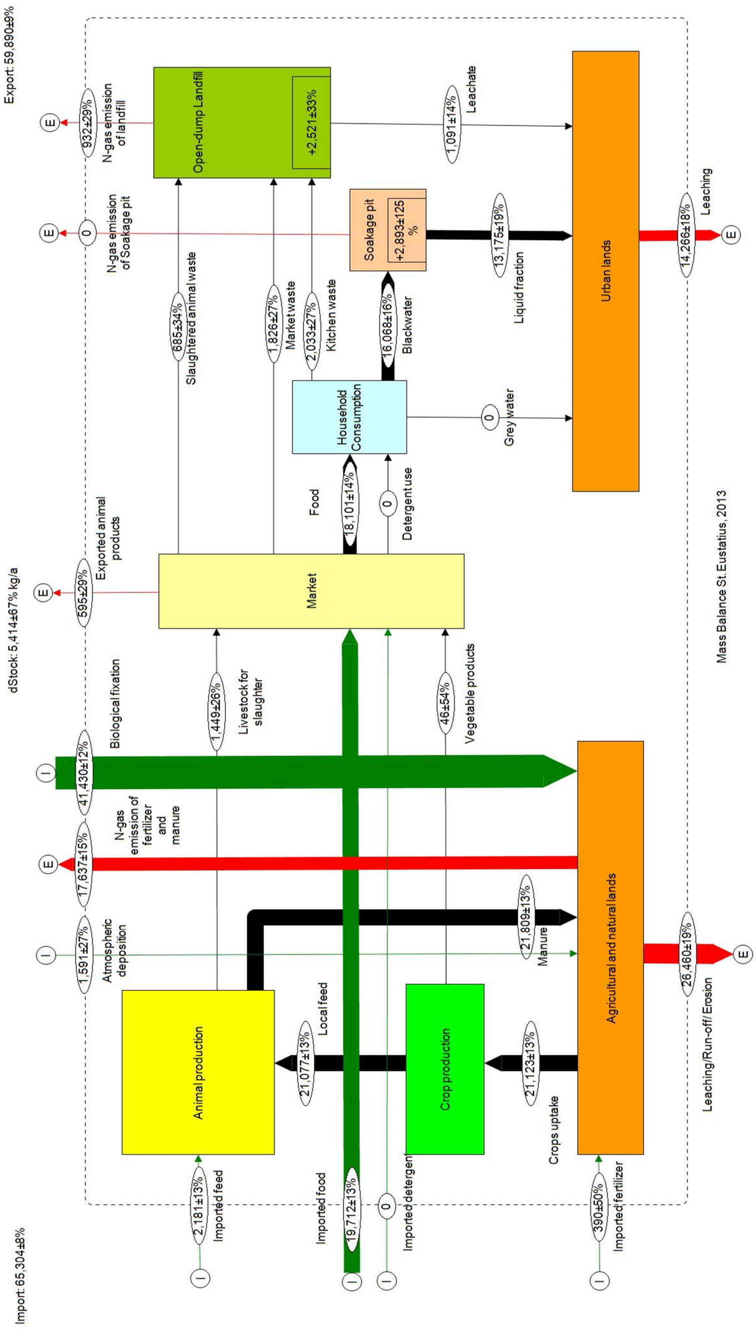

Figure 2.3 The flows and stock change of N in St. Eustatius (kg N/year)

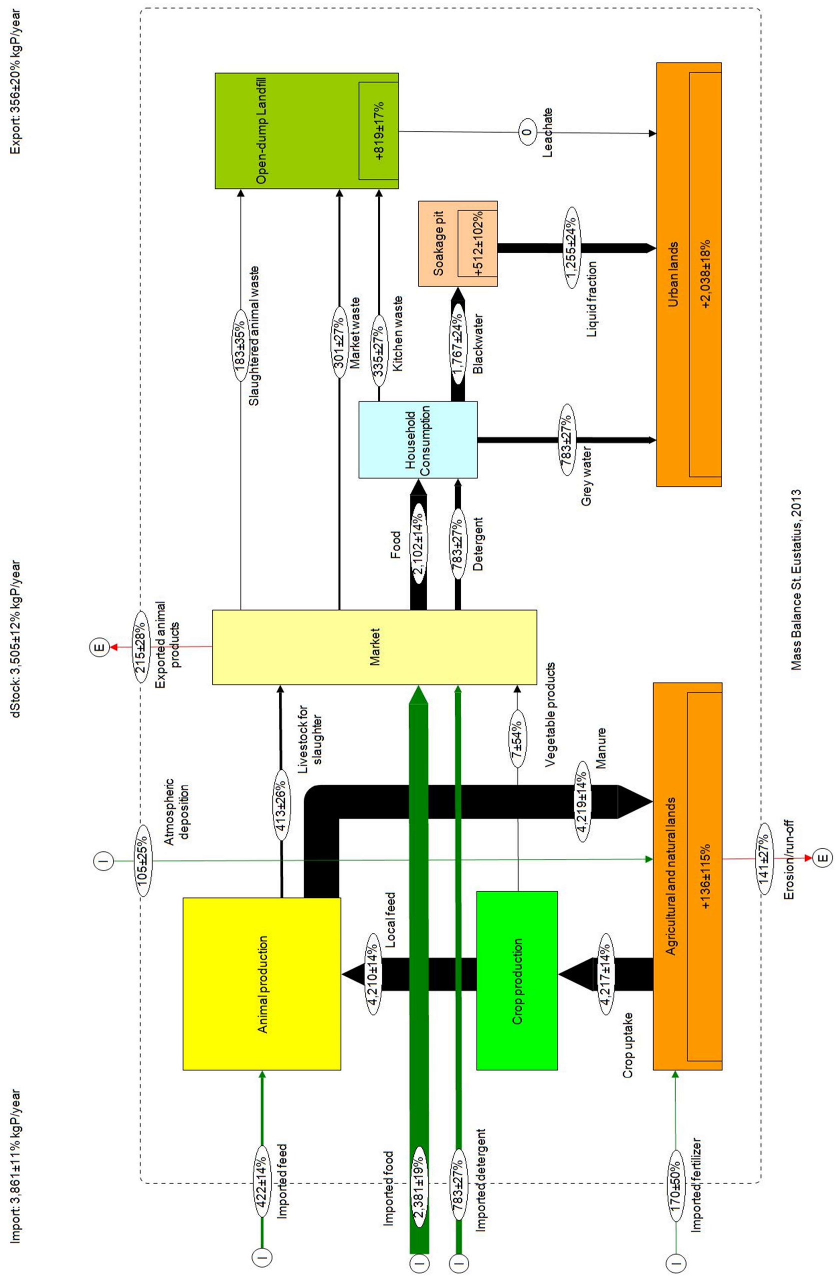

Figure 2.4 The flows and stock change of P in St. Eustatius (kg P/year)

2.4 Discussion

2.4.1 Comparison with other SFA studies

Comparison of the results with other SFA studies shows that the results for St. Eustatius are not well comparable (Table 2.3). Only for the Net stock for P are the values comparable. These differences indicate the specific characteristics of small islands such as St. Eustatius. The very low agricultural input and the very low imported mineral fertilizer (N&P) provide evidence for the subsistence agriculture on the island. Even compared to cities such as Bangkok, which have a relative high population compared to agricultural production and thus low per capita imports, the levels for St. Eustatius are low. This is not surprising as there are only about 3.6 ha of land currently farmed using mineral fertilizer. Table 2.3 also shows that there is no recovery of N and P from wastewater, which is another specific characteristic of St. Eustatius. However, at the same time the evidence shows that the stock increase for P is comparable to other cases studies, while the N stock increase even exceeds those of the two other studies available (only two studies). The reasons for this are related to high biological nitrogen fixation (BNF) on the island, in which high amounts of N are fixed by invasive species such as *Caesalpinia bonduc* and *Tamarind* (Smith et al., 2013). Other reasons are also related to the high meat diet and a direct discharge of the wastewater to the soil matrix (for P) that contributes to a high stock increase. In addition, this study includes a more detailed assessment of the "natural" N-cycle, to which other studies have not paid as much attention. In conclusions, the comparison shows that the variation between the present and other studies is large. However, a closer look at the data also shows that the variation between the other studies is large (Table 2.3 - e.g. Ma et al. (2010) for imported mineral fertilizer > 40 times this of Færge et al. (2001) and Meinzinger et al. (2009); Net stock for P Ma et al. (2010) almost 8 times higher than Færge et al. (2001)). This suggests that these substance flows are reflections of the socio-economic as well as natural conditions of each case (Fernandez-Mena et al., 2016, Voskamp et al., 2016).

Table 2.3 A comparison of results of this study with the results of other SFA studies for selected indicators: Net stocks (kgN/cap and kgP/cap) indicate accumulations within the analysed system including agricultural and natural soils, and urban soils; Agricultural input from mineral fertilizers (%) indicator measures how reliant the agricultural system is on mineral fertilizers; Imported mineral fertilizers (kgN/cap and kgP/cap) indicator measures the amount of imported mineral fertilizers; N and P recovery from wastewater (%) indicator reveals how much of the N and P from domestic waste and wastewater has been recovered and reused in agriculture as sludge, compost or other recovered products

SFA study location	Year	Net stocks		Agricultural input from mineral fertilizers (%)		Imported mineral fertilizer		N and P recovery from wastewater	
		N (kg N/cap)	P (kg P/cap)	% N	% P	kgN/cap	kgP/cap	% N	%P
China[1]	2005	0.46	2.62	61	69	20.70	3.80	-	-
Finland[2]	1995-1999	-	-	65	61	-	-	-	24.00
Arba-Minch, Ethiopia[3]	2009	-	-	67	-	0.50	0.18	-	-
Bangkok, Thailand[4]	1996	0.15	0.33	7	15	0.37	0.10	7.00	10.00
Haiphong, Vietnam[5]	2010	-	-	62	61	1.57	0.80	-	-
Netherlands[6]	2005	-	3.80	-	24	-	-	-	6.00
UK[7]	2009	-	1.90	-	27	-	1.02	-	41.00
St. Eustatius	2013	1.44	0.89	0.04	1.00	0.10	0.04	0	0

[1](Ma et al., 2010);[2](Antikainen et al., 2005); [3](Meinzinger et al., 2009); [4](Færge et al., 2001); [5](Aramaki and Thuy, 2010); [6](Smit et al., 2010); [7](Cooper and Carliell-Marquet, 2013)

2.4.2 Identification of intervention points

The results show that 57% of the N and 1% of the P are lost from the agricultural and natural land in St. Eustatius through leaching, nitrogenous gas emission and erosion/run-off. Most of the P accumulates in the urban land. The annual stock change for N in soakage pits, landfill and urban land is about 5400 kg or 14 times the annual fertilizer import or 2 times the combined feed and fertilizer import. For P, these numbers are even higher accounting for 20 times the fertilizer import and over 6 times the combined feed and fertilizer import. These numbers provide evidence that if only a small fraction of the nutrient flows on the island can be recovered and used, it would be sufficient to sustain the subsistence agriculture. At higher recovery rates, local food and feed production can be increased without increasing the dependency on fertilizer imports.

The system component that is the most likely place for recovery of these nutrients is the urban sanitation system, which consists of the soakage pits and the landfill sub-systems. Accumulation of N mainly takes place in the sanitation system, while P accumulation in the sanitation system contributes 37% to the total accumulation. About 58% of the remaining P accumulates in the urban land, and small percentage (5%) accumulates in the natural land. The P that accumulates in the urban soils might not be available to plants as the P is adsorbed below the root zone and cannot be released from the clay minerals. Contrary to this, P that accumulates in the sanitation system and especially in the soakage pits, is easily extractable in a concentrated form as pit sludge (de Graaff et al., 2011).

A further analysis of the key flows in the model enables the identification of other sub-systems for interventions that can improve nutrient management and reduce the environmental impact, such as eutrophication of the marine ecosystem, Green House Gas (GHG) emission and ground water pollution (Smith et al., 1999, Conley et al., 2009). However, while the soakage pit sludge can become a source of N and P, the major fraction of N and P is lost from this sub-system as liquids that enter the soil matrix. This does suggest that the current sanitation system needs modifications to enable maximal nutrient recovery.

The model also showed that animal and crop production sub-systems have large internal flows of N and especially P. These internal flows indicate that the nutrient cycle between crop uptake, feed and manure is largely closed. Most manure is from free roaming animals and this manure is assumed to be deposited where the animals graze. Some N losses take place, but these are compensated by biological fixation by plants. For P, feed consumption and manure excretion largely closes the cycle.

Figures 2.3 and 2.4 indicate that a large amount of N and P accumulates in the open-dump landfill sub-system. The open dump comprises a mixture of waste flows, which makes recovery of nutrients difficult. For nutrient recovery, important resource flows should be separated before they are mixed with other flows. Separating important resource flows at source may result in homogenous waste streams that can be more easily processed and reused. For example, slaughtered animal waste is such a homogenous stream. If slaughtered animal waste is diverted away from the landfill, specific treatment can be applied to enable safe recovery of N and P (Mata-Alvarez et al., 2000, Jensen et al., 2014).

4.3 Improved sanitation - interventions for improving nutrient management

As indicated above, the sanitation system was proposed as one of the most likely places for intervention to improve nutrient management on the island. Potential systems vary from low to highly advance and from centralized to a decentralized system, with multiple technological options all over the process train of collection, transport, treatment/recovery and reuse/disposal (Zeeman et al., 2008, Massoud et al., 2009, Tilley et al., 2014). For a small island like St. Eustatius, a viable treatment system that is low in capital and operating cost, compatible with the local expertise and institutional framework should be adopted.

Since the location of St. Eustatius is in the tropical region, anaerobic treatment, such as Septic Tank (ST), Upflow Anaerobic Sludge Bed (UASB), UASB-Septic Tank (UASB-ST) (Lettinga et al., 1993, Kujawa-Roeleveld et al., 2005, Zeeman et al., 2008), or Anaerobic Baffled Reactor (ABR) (Hahn and Figueroa, 2015), is a feasible option to improve existing sanitation treatment. The main treatment can be either applied house-on-site or community-on-site. As most households have a soakage pit, treating black water in a house-on-site UASB-ST or ST is relatively easy to install and will reduce emission to the soil and groundwater as these systems are closed. A UASB-ST is an improved conventional septic tank producing sludge, biogas, and a liquid effluent containing the majority of the nutrients. Liquid streams from the UASB-ST or ST could be transported to a community-on-site post-treatment for disinfection prior to reuse via a small bore sewer system (Mara et al., 2007), while the producing solid streams (sludge) can be collected by truck, post-composted with kitchen waste and used in agriculture as an organic fertilizer. Such measures will substantially reduce emissions and limit accumulation stocks. Alternatively, the black water can be transported via a conventional sewer system to a community-on-site UASB or ABR system. Such community-on-site anaerobic treatment system might enlarge the possibilities for biogas use and therefore the reduction of GHG emissions. However, a drawback of the necessary conventional sewer system is the high costs (Mara et al., 2007).

Additional intervention could be the recovery of struvite from the liquid rich-nutrient effluent of UASB or UASB-ST at community-on-site (de Graaff et al., 2011). Struvite ($MgNH_4PO_4$-$6H_2O$) is a product that can be recovered from concentrated domestic wastewater streams using precipitation technology with the addition of Magnesium (Mg) to recover P (Le Corre et al., 2009, Etter et al., 2011). It can be applied as a good hygienically safe slow release fertilizer (Le Corre et al., 2009, Cordell et al., 2011, Rahman et al., 2014). In the context of St. Eustatius, the liquid effluent of the community- or house-on-site anaerobic treatment system can, instead of direct use (after disinfection) in agriculture also be utilized for struvite recovery. However, this type of intervention is complex and expensive under the conditions prevailing at St. Eustatius, as the existing toilet need to be adjusted to provide a more concentrated blackwater and chemicals, such as $MgCl_2$, MgO, or $Mg(OH)_2$, are needed for struvite precipitation (Rahman et al., 2014).

Another possibility is the treatment and recovery of grey water with its included nutrients. The grey water of St. Eustatius is a substantial source of P (10 % of total input P). Greywater has a potential as irrigation/fertilisation water, and this resource could be exploited when diverting greywater to agriculture (Al-Hamaiedeh and Bino, 2010). However, using greywater as irrigation water for agriculture might be a challenge due to the spatial separation of agriculture and housing, but it may be feasible by promoting home gardening for the production of fruits and vegetables. The quantification model also reveals that the P in greywater originates from P in detergents. This implies that possible changes in policy or phasing out of P containing detergents may result in less environmental pressure, but also make this P from detergents a risky resource to rely on in future.

2.4.4 Impact of interventions towards nutrient recovery

Several sanitation concepts or interventions that can be applied in the context of St. Eustatius will have an impact on the nutrient recovery and reuse. Fig. 2 and Fig. 3 illustrate that the N and P containing sludge, retained in the soakage pit, can replace the currently imported fertilizer used in agriculture. About 3758 kg N/year and 439 kg P/year are available in the soakage pit that can be reused in agriculture. However, direct reuse of pit sludge in agriculture is not recommended as it still has high pathogens and micro-pollutants content.

Another concept is the application of UASB-ST to replace the soakage pits. According to literature, approximately 80% of N and 40% of P will end in the liquid effluent, while the remainder of the N and the remainder of P will end in the sludge (Kujawa-Roeleveld et al., 2005). Implementation of this concept in St. Eustatius will result in 14,000 kg N/year and 760 kg P/year remaining in the effluent, while almost 2000 kg N/year and 1400 kg P/year remaining in the sludge. As a next step, the sludge of UASB-ST can be co-composted with organic waste streams (eg. garden waste) to increase the organic matter content of the product in the form of compost for reuse.

Implementation of source-separation concept at household level will also have an impact on the nutrient recovery and reuse. If kitchen waste is separately collected from household, about 4800 kg N/year and 800 kg P/year can be treated together with wastewater (sludge) as proposed by (Larsen et al., 2009, Zeeman, 2012). Thereby, the collection and treatment of kitchen waste will reduce the amount of waste transferred to the open-dump landfill, reduce the N leachate from the landfill, and potentially improve groundwater quality. Moreover, separating urine from blackwater streams at the household level, collecting and treating it for reuse in agriculture will potentially recover 72% of N contained in urine (Larsen et al., 2009). This concept will result in higher nutrient recovery, improving wastewater effluent quality due to lower nutrient concentration in wastewater (Maurer et al., 2003). However, the collected urine needs to be stored at least six months for disinfection to increase the safety use of the urine (WHO, 2006).

The impact on the urban-agricultural system of any technological intervention can be assessed just as it was done for the present sanitation system in St Eustatius. In this way, the largely literature-based model developed in this study allows researchers and planners to first identify the point source of nutrient losses and secondly evaluate the potential interventions for better nutrient management. However, potential interventions for resource recovery also need to be assessed in the context of uncertainties about future developments, such as climate change, societal change, and economic change. These developments may influence both the nutrient balance and the potential applicability and effectiveness of the interventions. Scenarios have been widely applied to deal with uncertainty of future circumstances (Börjeson et al., 2006), for example by building normative scenarios (van der Voorn et al., 2012), or through trend analysis and building explorative scenarios (Van Vuuren et al., 2010, Gerland et al., 2014). Future research should aim to assess the performance of different sanitation technologies under different future development scenarios, by analysing global and regional trends and designing external scenarios.

2.5 Conclusions

The SFA approach developed in this study is considered as a first step to analyse the actual problems related to nutrient management. As a next step, it allows for the identification of critical intervention points and mitigation strategies for reducing N and P nutrient taking urban-rural development policies on the island into account. Moreover, the results indicate that most N and P loss in St. Eustatius is through erosion/run-off, leaching and gas emission. Accumulation of N and P takes place in the soakage pit and open-dump landfill. These stocks are currently lost and not reused in agricultural. Applying a specific intervention to replace the current sanitation system will have a systemic impact on the overall nutrient balance of St. Eustatius. Planners can therefore use this model to make decisions about future interventions for a transition to closing nutrient cycles.

Although the developed model provides N and P balances for the case of St. Eustatius, the approach presented can be applied in other small island systems that face limited data situation. Indeed, most of the resources and methods used in this study do provide important elements that can be adopted for integrated assessment of cities and hinterlands.

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CHAPTER 3

An integrated assessment of environmental, economic, social and technological parameters of source separated and conventional sanitation concepts: A contribution to sustainability analysis

I. Firmansyah[a], G.J. Carsjens[b], F.J. de Ruijter[c], G. Zeeman[a,d], M. Spiller[e]

[a]Wageningen University & Research, Sub-department of Environmental Technology, Bornse Weilanden 9, 6708 WG, Wageningen, the Netherlands
[b]Wageningen University & Research, Landscape Architecture and Spatial Planning, P.O. Box 47, 6700 AA, Wageningen, the Netherlands
[c]Wageningen University & Research, Agrosystems Research, P.O. Box 616, 6700 AP, Wageningen, the Netherlands
[d]Leaf BV P.O. Box 500, 6700 AM, Wageningen, the Netherlands
[e]Research Group of Sustainable Energy, Air and Water Technology, Department of Bioscience Engineering, University of Antwerp, Groenenborgerlaan 171, 2020 Antwerpen, Belgium

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Abstract
Resource recovery and reuse from domestic wastewater has become an important subject for the current development of sanitation technologies and infrastructures. Different technologies are available and combined into sanitation concepts, with different performances. This study provides a methodological approach to evaluate the sustainability of these sanitation concepts with focus on resource recovery and reuse. St. Eustatius, a small tropical island in the Caribbean, was used as a case study for the evaluation. Three source separation-community-on-site and two combined sewerage island-scale concepts were selected and compared in terms of environmental (net energy use, nutrient recovery/reuse, BOD/COD, pathogens, and GHG emission, land use), economic (CAPEX and OPEX), social cultural (acceptance, required competences and education), and technological (flexibility/adaptability, reliability/continuity of service) indicators. The best performing concept, is the application of Upflow Anaerobic Sludge Bed (UASB) and Trickling Filter (TF) at island level for combined domestic wastewater treatment with subsequent reuse in agriculture. Its overall average normalised score across the four categories (i.e., average of average per category) is about 15% (0.85) higher than the values of the remaining systems and with a score of 0.73 (conventional activated sludge – centralised level), 0.77 (UASB-septic tank (ST)), 0.76 (UASB-TF - community level), and 0.75 (ST - household level). The higher score of the UASB-TF at community level is mainly due to much better performance in the environmental and economic categories. In conclusion, the case study provides a methodological approach that can support urban planning and decision-making in selecting more sustainable sanitation concepts, allowing resource recovery and reuse in small island context or in other contexts.

Key words: sustainability, nutrients, holistic, urban, sanitation, recovery.

3.1 Introduction

Current developments of sanitation infrastructure have moved away from the focus on end of pipe treatment to the recovery of water, energy and nutrients for agriculture from wastewater. In this way future sanitation systems do contribute to the achievement of Sustainable Development Goals (SDGs) related to clean water and sanitation (SDG 6) and other SDGs targets such as clean zero hunger (SDG 2), and sustainable consumption and production (SDG 12) (Andersson et al., 2016).

Two basic concepts for resource recovery from wastewater can be distinguished. Firstly, the recovery of water, energy and nutrients from municipal wastewater that is collected and transported in a conventional combined sewer and treated in a centralised treatment (Lee et al., 2013), for example, a Conventional Activated Sludge (CAS) treatment or an Upflow Anaerobic Sludge Blanket (UASB) reactor (Noyola et al., 2012). The second alternative is source separated sanitation (Zeeman, 2012). While many variations of separation at source exist, one common approach is to collect Black Water (BW, the mixture of urine, faeces, and flushing water) and Grey Water (GW, laundry, shower, bath and kitchen water) in two piping systems and treat them separately. Furthermore, source separated sanitation concepts often encompass the collection and management of Kitchen Waste (KW), which increases biogas yields (de Graaff et al., 2010).

Source separated sanitation is a system that enables a more (energy) efficient recovery of resources from BW or urine while GW remains relatively low in pollutants. Source separated sanitation is explored and applied as a promising alternative where currently no traditional combined sanitation infrastructure is in place, for instance, in developing countries which have yet to develop sanitation infrastructure (Bisschops et al., 2019). In cases where local economies face water shortage and high costs for agricultural inputs such as fertilisers, source separated sanitation is deemed appropriate to maximise the reuse of water and nutrients while also recovering energy (Larsen et al., 2013, Sharma and Sanghi, 2013). While this applies to developing countries, it might even be more applicable to small islands, where fresh water is typically scarce and agricultural goods such as food and fertiliser are imported (Saint Ville et al., 2015).

As the diversity of sanitation systems grows, a challenge current and future decision makers will face is which sanitation system to select and, maybe more importantly, which aspects to consider when selecting a sanitation system (Spuhler et al., 2020). This entails to find the most sustainable combination of technologies and sewer infrastructure (in the following called sanitation concept) in a given context. Similarly, it has been shown that a well-structured approach to sanitation planning can make decision variables of actors more explicit and hence lead to better decision outcomes in complex situations (Haag et al., 2019).

In this research it is proposed that the selection of a ’sustainable’ sanitation system should cover the four dimensions of sustainability namely environmental, social-cultural, economic and technological. The first three dimensions are commonly described as the triple bottom line of sustainability, while the technological dimension has been proposed as especially important to sanitation systems (Spiller, 2016). The four dimensions need to be assessed across the entire technology train of each sanitation concept (i.e., from user interface to reuse) and include the aspects water reuse and nutrient reuse. However, due to the many indicators inherent in these four dimensions and the complexities of technological concepts, assessments so far are mainly partial. Previous authors are omitting parts of the technology train, such as sewer systems, or not covering all sustainability dimensions, required for a holistic appraisal. A majority of studies focuses on environmental assessments only (Kjerstadius et al., 2015, Prado et al., 2020). A number of studies also include economic aspects. Recent examples of this are Dewalkar and Shastri (2020) who provided an environmental and economic assessment of an on-site wastewater management system in a multi-storey residential building, while Chrispim et al. (2020) was focusing on the resource recovery at a centralized Wastewater Treatment Plant (WWTP).

One of the few approaches that addresses the increasing diversity of sanitation concepts is Spuhler et al. (2020). They developed a software tool (Santiago: SANitation sysTem Alternative GeneratOr) that enables the screening of 41 sanitation technologies and 27 selection criteria to generate a set of sanitation systems. However, in their publication, they do not provide a detailed account for the performance of different technologies along the four sustainability dimensions proposed in this research. Moreover, Spuhler et al. (2021) only focused on the environmental quantification of sanitation systems without considering social-economic indicators.

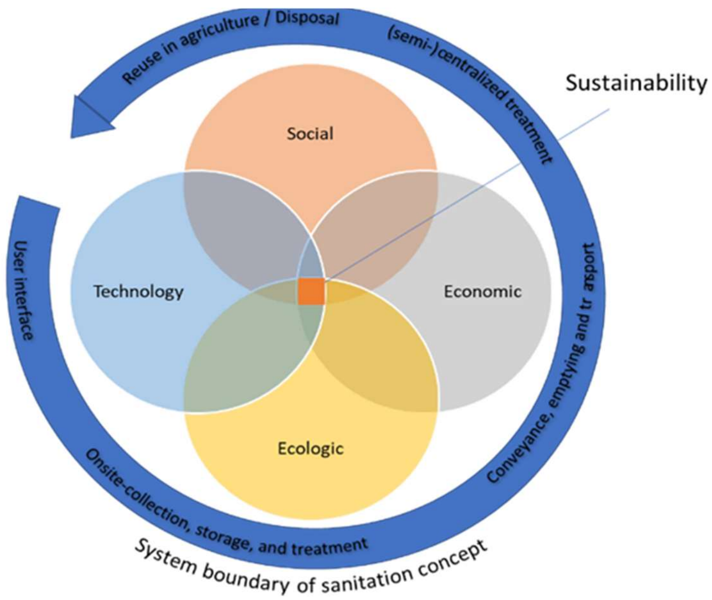

Figure 3.1 Underlying theoretical framework of sustainable sanitation systems

Following the considerations above, the aim of this study is to develop an approach to evaluate the sustainability of sanitation concepts that include the full train of technology from collection, transport, treatment/recovery, to reuse in agriculture or final disposal across different sustainability indicators (Figure 3.1). The approach is intended to provide quantification methods that combine quantitative and qualitative assessment of sustainability indicators. The evaluation has been carried out for the case of a small developing tropical island system (St. Eustatius). Although the selected sanitation concepts in this study are case and context specific (e.g., tropical), the general approach adopted is relevant for a wide range of other contexts.

3.2 Methodology

3.2.1 Description of study area

St. Eustatius is a small island located in the Caribbean, with a total population of 3877 in 2015 and an average number of 2.0 people per household (CBS, 2015). The total area is 2109 ha and the total urban area is 191 ha, in which houses are scattered on the island in approximately five neighbourhood areas (Smith et al., 2013, Firmansyah et al., 2017) (Figure 3.2). Soakage pits are the commonly applied technology for BW treatment, and untreated GW is discharged to the open ground or used for gardening. The disposal of collected solid household waste in an open landfill causes environmental pollution as untreated wastewater and organic waste emit nutrients and greenhouse gases (GHG) that contribute to environmental pollution (Firmansyah et al., 2017) – (Table 3.1).

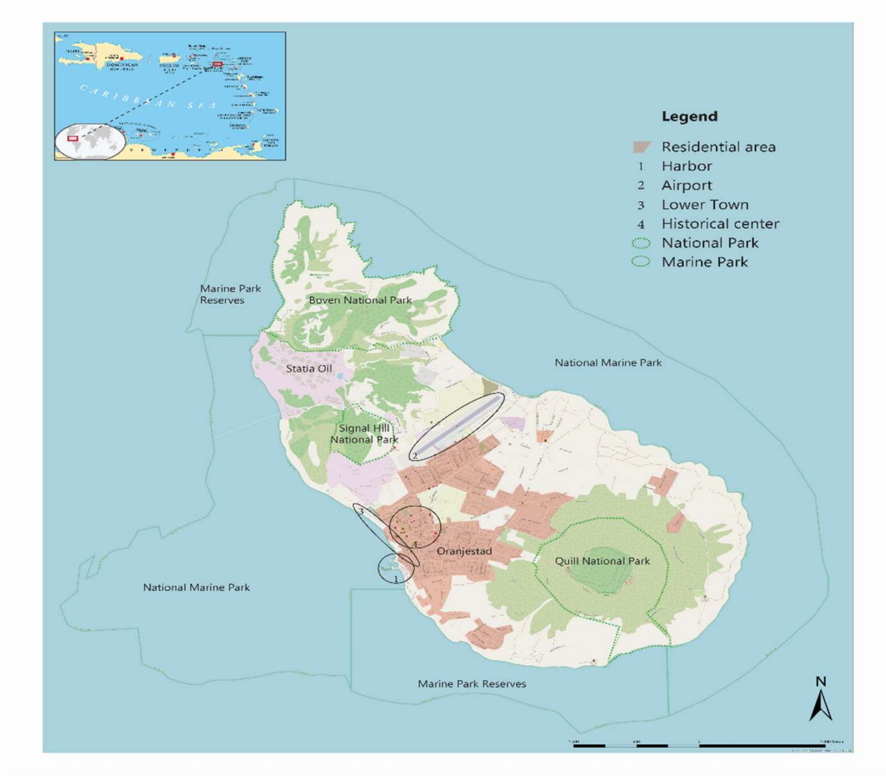

Figure 3.2 Map of St. Eustatius adapted from (Hoogenboezem-Lanslots et al., 2010).

Table 3.1 Characteristics of wastewater constituents generated at household level in St. Eustatius

Parameters	Unit	BW	GW	KW
Volume	L/cap/d	34[1]	117[1]	0.25[5]
BOD_5	g/cap/d	24[3]	16[3]	37[2]
COD[a]	g/cap/d	48[4]	32[4]	59[2]
TN	g/cap/d	11.2[5]	1.2[2]	1.4[5]
TP	g/cap/d	1.2[5]	0.5[5]	0.2[5]
Faecal Coliforms (FC)	CFU/100 ml	8 log[6]	5 log[7]	0

Source: [1](Ghisi and Ferreira, 2007), [2](Kujawa-Roeleveld et al., 2005), [3]calculated based on total BOD of domestic wastewater of Latin America and Caribbean (LAC) countries (IPCC, 2006) and GW/BW ratio of 1.5 (Kerstens et al., 2015), [4]COD/BOD was calculated based on ratio of 2 (Meinzinger and Oldenburg, 2009), [5](Firmansyah et al., 2017), [6](Metcalf et al., 2003), [7](Finley et al., 2009).

3.2.2 Research approach

The research approach developed in this study is depicted in Figure 3.3. The steps include:

(1) Selected suitable sanitation concepts – The selected concepts are based on a review of scientific literature and local conditions. The selection process includes iterations of drafting, redrafting and discussion of flow diagrams of sanitation concepts.

(2) Selected criteria for sustainability evaluation - The selected criteria are based on the most commonly used sustainability indicators in scientific literature and an assessment by sanitation experts.

(3) Assessment of performance – The performance of sanitation concepts includes quantitative and qualitative indicators, which are evaluated using scientific literatures and an assessment by sanitation experts.

(4) Ranking sanitation concepts – The sum of normalized indicator values is applied to rank the performance of sanitation concepts.

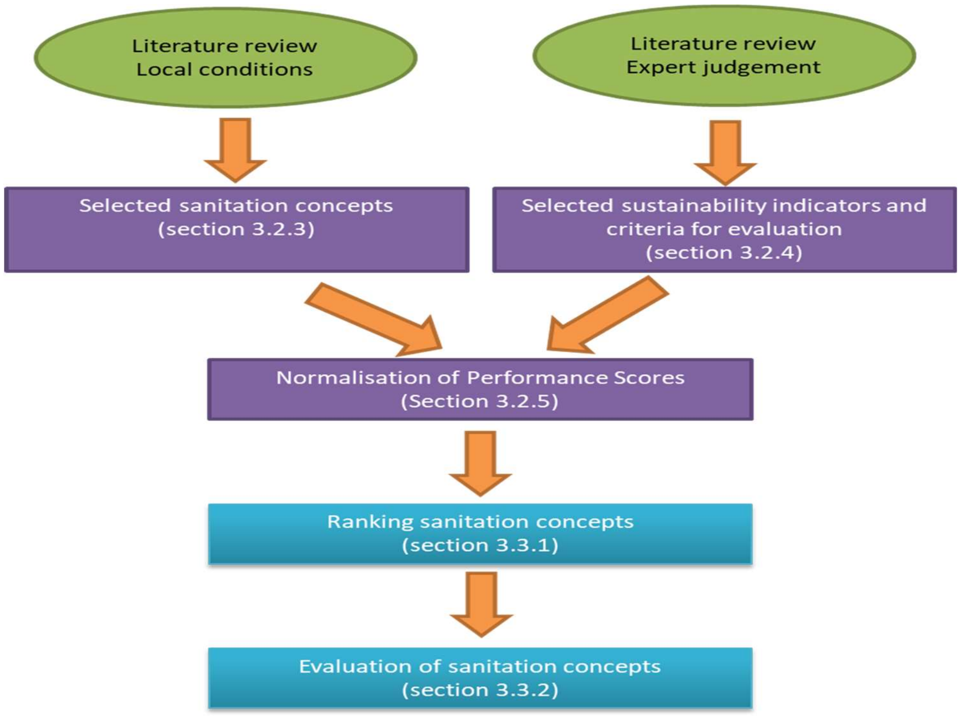

Figure 3.3 Methodological framework for assessment and ranking of the performance of sanitation concepts

3.2.3 Selected sanitation concepts

Following an extensive study of the literature and considering local tropical conditions, the sanitation concepts selected in this study are described and portrayed in Figure 3.4. The key rationale for technology selection was to maximise the use of current infrastructure and to use simple and robust (i.e., easily installed, functional under a range of conditions) infrastructure. Furthermore, it was also aimed to benchmark source separation technologies against the more common forms of collection, transport, and treatment. Therefore, ST, TF, CW, CAS and UASB have been included in the comparison, which are the most commonly applied wastewater treatment systems in LAC countries (Noyola et al., 2012). Low-flush toilets (user interface) are applied at all sanitation concepts.

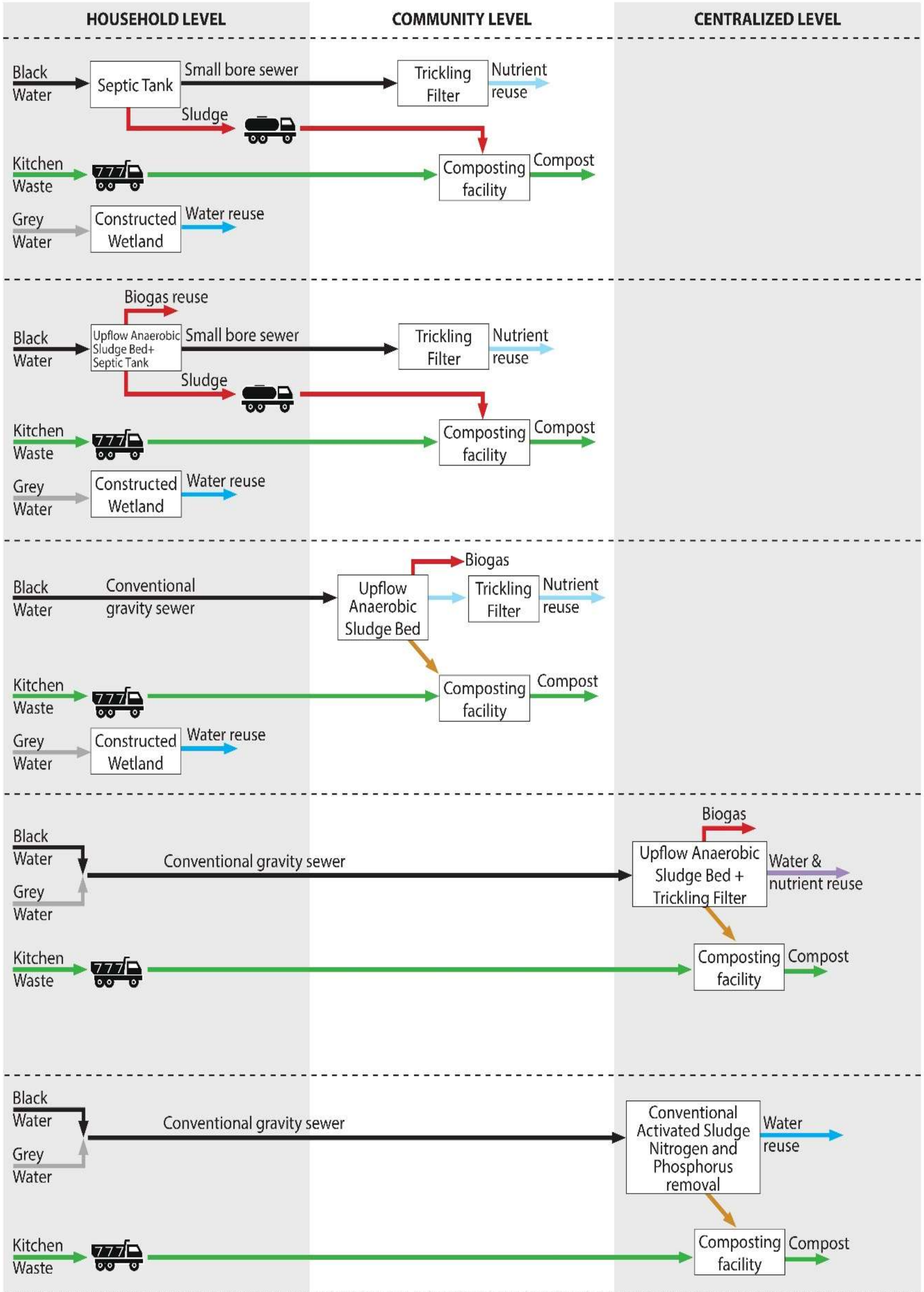

Figure 3.4 Graphical representation of the sanitation concepts selected for comparison with different application of treatment technology; see Supplementary Material (SM) section S2.1 for detailed explanation.

3.2.4 Selected sustainability indicators

Four different sustainability domains need to be evaluated to arrive at a comprehensive assessment, including technological, environmental, economic, and societal-cultural aspects (Balkema et al., 2002, Muga and Mihelcic, 2008). Preliminary selection of (qualitative and quantitative) indicators is based on the most cited indicators in scientific literature (Spiller, 2016). A final list of indicators and their criteria of evaluation are identified using literature review and expert judgment. However, the approach presented in the study provides flexibility for the final selection of the indicators depending on the studied areas. The selected sustainability indicators are shown in SM Section S2.2.

3.2.4.1 Net energy use

Net energy use (kJ/cap per day) was calculated based on the difference between energy production and consumption. The energy consumption per sanitation concept includes the energy requirement for the collection and transport of BW, GW, KW and sludge, as well as the treatment process. The methodology for calculating energy requirement and production are shown in Table 3.2.

Table 3.2 Methodologies applied to calculate energy requirement and production per concept

Description	Methodology	Concepts
Transport	20 kWh/cap per year (for a pumping station) (van Buuren, 2010)	4, 5
	4.8 MJ/t/km^2; 1 km (van Buuren, 2010) for sludge	1,2,3
	4.8 MJ/t/km^2; 5 km (van Buuren, 2010) for KW	4,5
Treatment	2.2 MJ/kg COD removed and 14 MJ/kgN removed, 5 MJ/kg P removed (Maurer et al., 2003)	5
	104.4 MJ/t for turning compost (Henze et al., 2008)	1,2,3,4,5
Production	0.35 m^3 CH_4/kg COD converted; anaerobic biodegradability of BW (71%) (Elmitwalli et al., 2001)	2,3
	0.35 m^3 CH_4/kg COD converted; anaerobic biodegradability of BW and GW (74%) (Elmitwalli et al., 2001)	4

3.2.4.2 Nutrient recovery

The amount of nutrients recovered in each sanitation concept was calculated based on the removal efficiency of the treatment technologies as reported in literature (Table 3.3). Since the literature based removal efficiencies show some variabilities, an average of the different values found has been derived for calculation in this study (SM section S2.3). Since the sludge produced in each concept is co-composted with KW, the nutrient recovery and reuse indicator of compost was calculated based on the amount of TN and TP remaining in the sludge and KW (SM section S2.4).

Table 3.3 Removal efficiencies of selected sanitation concepts for comparison. The removal efficiency describes the reduction of the relevant concentrations in the liquid phase (details in SM section S2.3)

Parameter	**Concept 1**		**Concept 2**		**Concept 3**		**Concept 4**	**Concept 5**
	BW	GW	BW	GW	BW	GW	BW+GW	BW+GW
	ST+ TF	CW	UASB-ST+TF	CW	UASB +TF	CW	UASB +TF	CAS+N/P removal
BOD	95%	93%	97%	93%	97%	93%	87%	98%
COD	91%	79%	95%	79%	87%	79%	82%	92%
TN	27%	67%	27%	67%	27%	67%	27%	80%
TP	5%	65%	5%	65%	5%	65%	5%	82%
FC	2 log	4.8 log	4 log	4.8 log	4 log	4.8 log	4 log	4 log

3.2.4.3 GHG emissions

Direct GHG emissions were calculated based on the amount of CO_2, CH_4 and N_2O produced during wastewater treatment. Whilst the indirect GHG emission (CO_2) was calculated based on the energy demand for wastewater treatment or transportation of sludge. CO_2 emissions as a result of biological conversion were not included, because it is considered short cycle CO_2 (i.e., from biogenic sources (Heffernan et al., 2012)). The amount of GHG emissions emitted were converted into the CO_2 equivalent emissions in each sanitation concept (CH_4 = 21 and N_2O = 310) (IPCC, 2006). Methodologies applied to calculate GHG emission can be seen in Table 3.4 below.

Table 3.4 Methodologies applied to calculate GHG emission

Description	Methodology	Concepts
CO_2 emission	725 gCO_2/ kWh for electricity from diesel oil combustion (IEA, 2015)	1,2,3
	1594 gCO_2/L diesel with a diesel demand of 0.33 l/km of a 2 m^3 truck for sludge transport	1,2
CH_4 emission	0.35 m^3/kg COD removed; anaerobic biodegradability of BW (71%) for ST	1
	0.35 m^3/kg COD removed; a correction factor of 0.01 for VSSF wetlands for CW	1,2,3
	Dissolved CH_4 in the effluent, in the range of 18 to 22 mg/l (Souza et al., 2011)	2,3,4
N_2O emission	0.016 kgN_2O-N/kgN (IPCC, 2019) for TF and CAS	1,2,3,4,5
	0.00023 kgN_2O-N/kgN (IPCC, 2006) for CW	1,2,3
	2.5% of the initial N content are converted to N_2O gas in a composting plant (IPCC, 2006)	1,2,3

3.2.4.4 Land area requirement

For source-separation concepts (concept 1, 2 and 3), the land area requirement was calculated from the typical Organic Loading Rate (OLR) of ST, UASB and UASB-ST as well as TF. For GW treatment at household level using CW, the total land area was calculated based on the methodology described by UN-HABITAT (2008). For centralized concepts, the total land area included the land area of UASB and TF (concept 4) or CAS system (concept 5) including secondary clarifier (Tervahauta et al., 2013) (SM section S2.5).

3.2.4.5 CAPEX and OPEX

The Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) for sewer system, treatment system and land use were included in the assessment. The methodologies for the calculation were based on several references that can be seen in Table 3.5.

Table 3.5 List of methodologies to calculate CAPEX and OPEX

Description	Methodology		Concepts
	CAPEX	OPEX	
Sewer system	small bore sewer: €120-140 per person; includes material and labour costs	Cleaning pipes	1,2
	conventional gravity sewer:(Maurer et al., 2013)	Cleaning pipes	3,4,5
	manholes and pumping station	Electricity costs for pumping the wastewater in a pumping station was calculated based on the energy use (20 kWh of a pumping station with wet sump installation and a capacity of 60 m3/h), maintenance was calculated with 5% of the mechanical and electrical costs and 2.5% of the construction costs	4,5
Treatment system	empirical cost functions using commercial cost models from DESAH BV and RoyalHaskoningDHV (Roefs et al., 2017)	(0.5% of total civil engineering costs plus 1.5% of total mechanical engineering costs), while chemicals, laboratory costs, and sludge handling were not included	3,4,5
	ST based on (Loetscher and Keller, 2002)		1
	UASB-ST based on (van Buuren, 2010)		2
	TF based on (Gratziou et al., 2006)		1,2,3,4
	CW based on (Nanninga, 2011)		1,2,3
	Composting facilities based on (Wei et al., 2001)		1,2,3,4,5
Land use	52 Euro/m^2 (van den Bergh, 2013)		1,2,3,4,5

The detailed methodology of the sewer system calculation, including CAPEX and OPEX, can be seen in SM Section S2.6. Calculation of the treatment system can be accessed in SM section S2.7.

In order to compare the CAPEX of all sanitation concepts over their planning period, the CAPEX was calculated using Net Present Value (NPV) (Equation 1) (Maurer, 2009).

$$CAPEX\ (\frac{Euro}{cap}\ per\ year) = \frac{\left[I * \frac{r(1+r)^{TD}}{(1+r)^{TD}-1} * T_D\right]}{Pt} \quad (1)$$

where, CAPEX (Euro/cap per year), I= investment cost, r = the discount factor of 5%, TD = planning horizon (20 years), and Pt=total population connected.

3.2.4.6 Qualitative indicators assessment

Four sustainability indicators were assessed using expert judgment: (1) The level of acceptance of a sanitation concept, (2) The required competences and education for implementing a sanitation concept, (3) Flexibility/adaptability of the technology and infrastructure to be changed, and (4) The reliability of the treatment system.

Five sanitation experts (three practitioners and two academics) from the Netherlands evaluated all sanitation concepts for these criteria. In a questionnaire, each criterion was scored along a five-point Likert scale from “bad” (1) to “good” performance (5).

3.2.5 Normalisation of performance scores

All evaluated indicators were normalised to enable an evaluation of the trade-off between different performance characteristics. To normalise, it was first decided whether a higher or a lower value was desired. For example, for N recovery a higher value is desired while for CAPEX a lower value is desired. Thereafter, a simple normalisation method was used for each individual score (Equation 2 and 3):

Max. values: $r_{ij} = \frac{x_{ij}}{max_{ij}}, i = 1, \ldots, m; j = 1, \ldots, n$ (2)

Min. values: $r_{ij} = -\left(\frac{min_{ij}}{x_{ij}}\right) \div -1, i = 1, \ldots, m; j = 1, \ldots, n$ (3)

where r_{ij} is the normalised score, for *i* indicator in *j* sanitation concept, and there are m indicators and *n* sanitation concepts.

For each of the four sustainability categories the average of the normalised values was determined and subsequently summed over the four categories to arrive at a total score, with higher values representing a better score.

3.2.6 Sensitivity Analysis

A sensitivity analysis was performed to determine the impact of uncertainties on the performance of sanitation concepts. Parameters such as removal efficiencies of BOD, COD, TN, TP, and pathogens, N_2O emissions, as well as the qualitative indicators were selected to assess the overall performance of each sanitation concept by using 1000 Monte Carlo simulation runs and uniform distribution between minimum and maximum values (SM Section S2.8).

3.3 Results and Discussion

3.3.1 Ranking of sanitation concepts

The comparison of normalised values for all indicators shows that the centralized concept with UASB and TF treatment (concept 4) has the highest overall performance (Figure 3.5). Its overall average across the four categories (i.e., average of average per category) is about 15% (0.85) higher than the values of the remaining systems and with a score of 0.72 (concept 5), 0.77 (concept 2), 0.76 (concept 3), and 0.75 (concept 1). In particular, concept 4 has the highest overall performance in the category of environmental and economic indicators. In the following the reasons for the different performances of the sanitation systems are analysed.

3.3.1.1 Quantitative Indicators

Net energy use: The results show that the highest net energy production occurs in concept 4 (559.55 kJ/cap per day) followed by concepts 2 and 3 (424.59 and 363.73 kJ/cap per day, respectively) (Table 3.6). These concepts are all energy positive due to the application of anaerobic treatment (converting COD into CH_4), a low operational energy demand and suitable warm conditions to promote anaerobic digestion without additional heating (Mainardis et al., 2020). As concept 4 receives about 1.6 times more COD, due to the addition of GW, it has the highest energy production. The additional energy generated from this can more than compensate for the higher energy demand (197.7 kJ/cap per day) for pumping of sewage. This finding is rather novel as most studies that investigate biogas production in WWTP (Shen et al., 2015), or as the recent study of Prado et al. (2020) do considered that biogas is flared without energy recovery. Finally, the highest total net energy use occurs in concept 5 (437.53 kJ/cap per day) mainly due to aeration in the CAS system and the necessity for pumping of sewage. Concept 1 (ST) has a net energy demand, because of sludge transport, energy for composting and absent biogas recovery (0.5 kJ/cap per day).

Nutrient recovery: For the nutrient (N and P) loads, it can be noted that the CAS system (concept 5) results in a loss of more than 70% of the N through the nitrification-denitrification process. The other systems have the advantage of conserving about 80% of the N thereby highlighting the relevance of alternatives to CAS in order to avoid Haber-Bosch N production and progress towards nutrient self-sufficiency (Verstraete and Vlaeminck, 2011). As a result of the high N removal efficiency, concept 5 scores the lowest in this category. All P contained in the wastewater is reused, either contained in the liquid or the solid fraction. Concept 4 has the highest TP load in the efflluent (1.9 gTP/cap per day), due to the low P removal in the UASB and the contribution of the GW (detergents contain P). Concept 5 has the lowest TP remaining in the effluent (0.2 gTP/cap per day) as most of P is diverted into the sludge in the enhanced biological phosphorus removal (1.7 gTP/cap per day). This however does not affect the overall assessment as the total recovery in water and solids is considered.

*BOD/COD:*The highest organic contamination of the effluent can be found in Concept 4 (5.3 gBOD/cap per day; 14.6 gCOD/cap per day). Concept 4 has a lower removal efficiency than concept 1 and 3. On the contrary, concept 5 has the lowest amount of COD due to the high removal efficiency of organics in the activated sludge (0.8 gBOD/cap per day; 6.4 gCOD/cap per day).

GHG emissions: Concept 5 has the highest GHG emissions of all concepts (0.45 kgCO_2-eq/cap per day), mainly attributable to the high net energy demand resulting in CO_2 emission and the nitrification-denitrification process resulting in high N_2O emission in the CAS system. In concepts 1-4, the mechanical composting and the TF contributed between 33 and 47% to the CO_2-eq emissions (see SM Table S2.15). Differences between GHG emissions (CO_2 and N_2O) during composting are the function of the sludge volume and therefore highest in concept 5 (0.1 kgCO_2-eq/cap per day).

*Pathogens:*The values of FC in the effluent of concepts 2-5 comply with the microbiological standard of WHO guidelines (WHO, 2006) for unrestricted and restricted irrigation in agriculture. The effluent of the concepts reaches 4 log removal. Concept 1 has the lowest performance due to the low pathogen removals in a ST. The application of fecal sludge and effluent from on-site technologies such as STs for reuse in agriculture provides a high risk to farmers as well as consumers in Uganda (Butte et al., 2021), and Chile (Livia et al., 2020). However, the application of fecal sludge that is co-composted with kitchen waste can reduce adequately enterobacterial pathogens and can inactivate parasites (Mulec et al., 2016).

CAPEX and OPEX:

Through economies of scale, the CAPEX of the centralised concepts 4 and 5 is nearly 33% lower when compared to the other decentralised concepts. For decentralised systems multiple infrastructures at household level and community level will be needed. This cannot be compensated by the relative cost efficiency of the small-bore sewer system and septic tank installations, applied in concept 1 and 2, (SM Table S2.16). Furthermore, the OPEX of concept 4 is the lowest compared to the other concepts, due to the efficiency of maintaining one installation and avoiding the household or community-based collection and transport of sludge. The OPEX for concept 5 is comparable to the decentralised systems due to the relatively high demand for energy. The higher costs of the decentralised systems have been described previously in literature (Roefs et al., 2017). However, it has been suggested that this balance may change if the recovery of nutrients and water would be accounted for in the cost estimations (Roefs et al., 2017).

Land Use:

Compared to the decentralised concepts (1-3), concept 4 only requires about 3% of the land use (0.04 m^2/cap), which is a bit less than the CAS system (concept 5, 0.06 m^2/cap). The reason for this is that concepts 1-3 apply CW which requires a higher land use due to a space demand of 0.97 m^2/cap (SM Table S2.17). The ST concept (concept 1) requires the highest area per capita (1.53 m^2/cap) due to the construction of many septic tanks. Comparing space demand values across literature is challenging as other authors do apply different process configuration (e.g., not including TF and composting). However, values for concept 5 are similar to those of Tervahauta et al. (2013) with an assumption that a CAS has a space demand of 5 m^3/m^2. Furthermore, the calculated footprint of CW in this research is not different with other researches. It was indicated that vertical flow CW systems has a large area footprint of 1-3 m^2/cap (Vymazal, 2011).

3.3.1.2 Qualitative Indicators

Acceptance:

Interviewees indicated that centralized concepts offer more convenient conditions for the users. In a centralized concept, the users are expected to be not directly involved with the operation and maintenance of the concept as it requires skilled operators. While in the decentralised concepts (concept 1 and 2), the users are responsible to maintain and control the treatment technologies, viz. the ST and UASB-ST at household level. Moreover, some interviewees suspected that anaerobic treatment applied in concept 1 to 4 creates odor nuisance. However, if properly managed odor is not a problem in a decentralised application (Kujawa-Roeleveld et al., 2005). Indeed, more recent research indicates 64% of a representative sample of Dutch citizens are willing to use decentralised sanitation (with a different technological setup), driven by environmental concerns and despite concerns related to the housing market and behavioural change (Poortvliet et al., 2018).

Competencies and education required:

The requirement of a high skill level for operation and maintenance of the centralized sanitation concepts has resulted in the lowest score for the concept 5 and followed by concept 4, while concepts 1 to 3 do not have a high demand on human resource skills. This was indicated with a consensus among interviewees that concept 1 has the highest score because the application of ST is renowned for its simplicity. No high skilled competency is required for the operation and maintenance of the technology. Compared to concept 1, the score is lower for concept 2 and 3. The application of a UASB-ST at household level and a UASB at community level is expected to require more knowledge on biogas handling and storage.

Flexibility/adaptability:

Decentralized concepts have advantages with regard to their simplicity of construction and changeability (Larsen et al., 2013). This argument is reflected in the performance score of the flexibility/adaptability indicator assessed by the interviewees. Concept 5 has the lowest score due to its complexity of the construction and operation. However, some interviewees indicated that concept 4 is the most complex system, because of the requirement of a centralized gas collection system. However, for the purpose of this analysis it was considered that the UASB of concept 4, is simpler to operate than a CAS system with biological nitrogen removal. Contrary to this, concept 1 has the highest score due to its simplicity on the construction of the ST and small-bore sewer system.

Reliability/continuity of service

Reliability/continuity service indicator reveals the capacity of the system to respond to the failures due to pipe blockage and power failures. The results showed that Concept 5 has the lowest score. If there is a blockage in the sewer system applied in the centralised concepts (concept 4 and 5), high level of maintenance is required which is more challenging compared to the sewer system applied in decentralised concepts (Concept 1 to 3). Concept 1 has the highest score as the concept also does not rely on electrical supply and it has the lowest impact if there is a failure in the system.

Table 3.6 Comparison of performance of the sanitation systems (for more detail see the SM section S2.9)

Category	Indicators	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Environmental	1. Net energy use (kJ/cap per day)	0.5	-423.9	-363.7	-362.3	437.53
	a. Energy consumption (kJ/cap per day)	0.5	0.7	0.01	197.7	437.53
	b. Energy production (kJ/cap per day)	0	424.59	363.73	559.55	0
	2. Nutrient recovery/reuse					
	a. TN recovery (gTN/cap per day)	10.6	10.6	10.6	11.1	4.4
	b. TP recovery (gTP/cap per day)	1.4	1.4	1.4	1.9	1.9
	3. BOD/COD in the effluent					
	a. BOD in the effluent (gBOD/cap per day)	2.4	1.9	3.7	5.3	0.8
	b. COD in the effluent (gCOD/cap per day)*	11.3	9.1	13	14.6	6.4
	4. Pathogen (CFU/100 ml)	1000000	10000	10000	10000	10000
	5. GHG emission ($kgCO_2$-eq/cap per day)	0.163	0.18	0.161	0.25	0.45
	a. CH_4 emission ($kgCH_4$/cap per day)	0.0016	0.0023	0.0023	0.00578	0.013
	b. N_2O emission (kgN_2O/cap per day)	0.000281	0.000286	0.000294	0.000337	0.000385
	c. CO_2 emission ($kgCO_2$/cap per day)	0.04247	0.04265	0.02239	0.02299	0.06545
	6. Land use (m^2/cap)	1.53	1.37	1.00	0.04	0.06

Continued on the next page

Table 3.6 Continued

Category	Indicators	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Economic	7. CAPEX (EUR/cap per year)	28.7	29.7	29.1	19.8	20.3
	8. OPEX (EUR/cap per year)	19.4	19.6	18.2	10.5	19.0
Social-Cultural	9. Acceptance	3.7	3.4	3.8	4.1	4.8
	10. Competences and education required	3.7	3.4	3.2	2.1	1.6
Technological	11. Flexibility/adaptability	4.2	4.0	3.7	3.2	2.9
	12. Reliability/continuity of service	3.4	3.5	3.4	3.0	2.8

*To prevent double counting in ranking the sanitation concepts, only COD in the effluent that was included in the normalisation

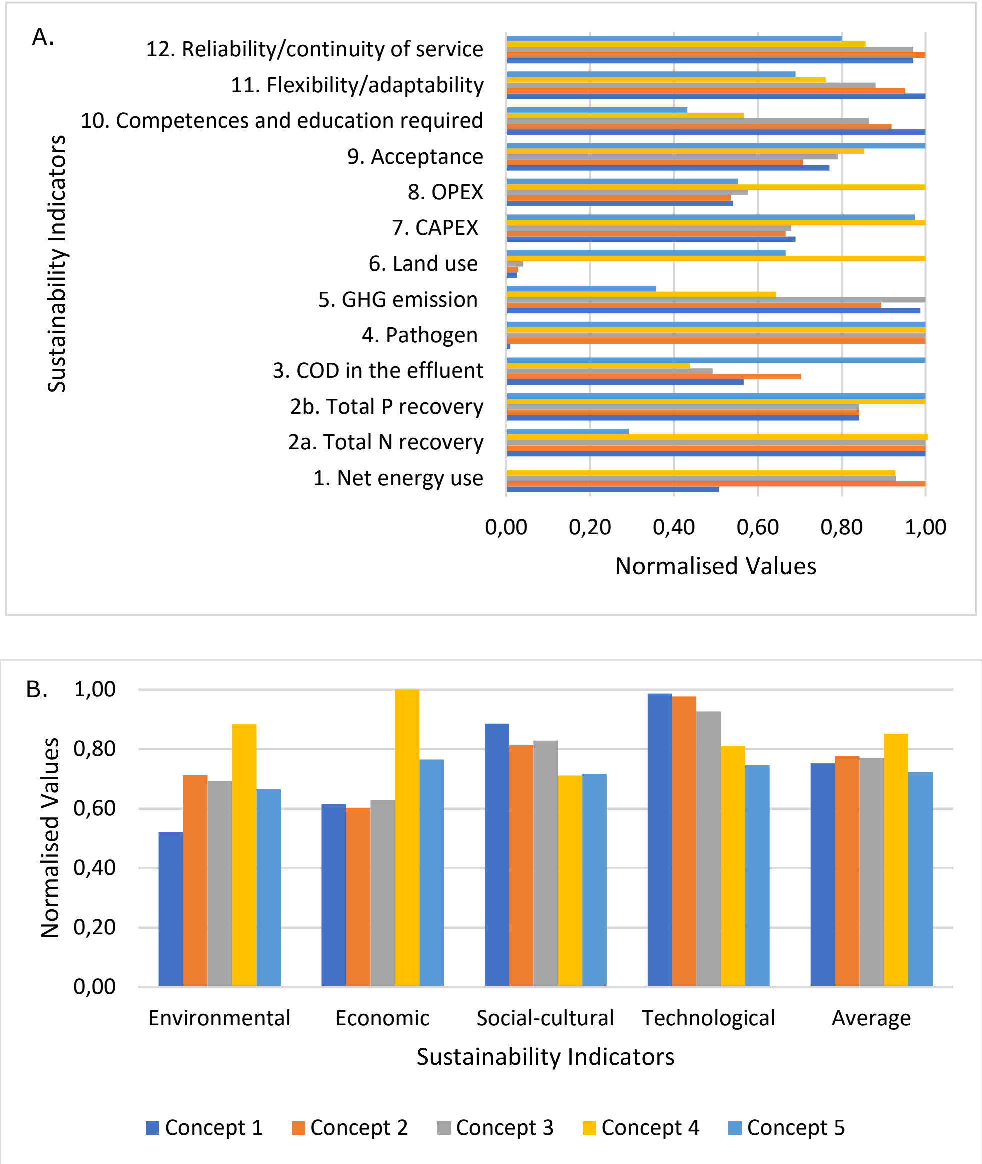

Figure 3.5 (A) Normalised values of the performance of sanitation concepts for all indicators; (B) per domains of sustainability indicators and average: Maximum value (1) indicates the best performance of sanitation concepts

3.3.2 Evaluation of the performance of sanitation concepts

The above analysis presents an attempt for a "rational" comparative evaluation of the different performances of sanitation systems, however the results and methods are, as every model, a simplification of reality. The end responsibility for a decision rests with decision makers and their advising experts. It is at this level that the evaluation presented here must be examined on a case by case basis. The decision can relate to the selection of the technologies, sustainability indicators, aspect of reuse, etc. Below we shed light on some of the potential aspects to take into further consideration and point towards other bodies of work that cover these topics.

3.3.2.1 The nutrient pathways

The present paper considers tropical conditions with a year-round cropping system. Nutrient recovery from the treated wastewater streams is in the form of liquid (effluent) and solid-based (compost) fertilizer. A decision on the type of fertilizer that can be effectively applied on agricultural fields is necessary to consider, as nutrients in the liquid fraction are readily available to plants, while the solid fraction is a slow release fertilizer (FAO, 2011). Since BW sludge has a lower heavy metal concentration as compared to conventional sewage sludge (Tervahauta et al., 2014), the source separation concepts 1, 2 and 3 are more attractive in this respect. In the present study, reuse of GW in agriculture in the source separation concepts is not included, but the decision for reuse is depending on personal interest at a household level. Alternatively, a community on-site CW could be applied with reuse of the effluent in agriculture. However, since P in GW mainly originates from detergents and the use of it is no longer allowed in a number of European countries (van Dijk et al., 2016), this route of P may not be accounted for in the future. The nutrients reuse indicator in each concept will change considerably.

3.3.2.2 Local conditions - Climate as a choice mediator

Local climatic condition can play an important role in the selection of technologies for implementation. One reason for the preference of municipal UASBs in most of the LAC countries is that they can function well in the tropical climatic conditions. In more temperate climates the costs of heating a diluted sewage are prohibitive for implementation of municipal UASB. Contrary to this, practical examples show that decentralised treatment of BW in a UASB reactor is feasible at a scale of 1200 people or more, when these reactors receive a concentrated BW produced by applying vacuum collection and transport (STOWA, 2014). However, in temperate climates, the reuse of the UASB effluents is not possible due to the seasonality of agricultural activities. In these conditions, UASB effluents are subjected to further refinement processes such as struvite precipitation and ammonia stripping for producing concentrated fertilisers (Bisschops et al., 2019).

3.3.2.3 Economics – allocation for costs and benefits between actors and development uncertainties

Sewer systems, centralised or decentralised treatment systems may be owned and operated by different insitutions, hence also resulting in a different distribution of the costs and benefits. For example, the costs of construction of STs are likely incurred by a private person as it will be constructed on their property, hence not requiring investment of public money (Kerstens et al., 2015). Due to the novelty of community based sanitation systems various organisational models can be envisioned, but it is likely that one party will own and operate the systems. Indeed, some authors suggest that new business and organisational models may emerge, where communities join to maintain, operate, and own a sewage treatment system (Hegger and van Vliet, 2010).

Another crucial aspect not accounted for in the presented evaluation is the development and change of sanitation systems over time. Using an NPV evaluation, Maurer (2009) and Roefs et al. (2017) have shown that decentralised sanitation with GW and BW separation can, when population growth is over estimated, be a more economic alternative. Indeed, more conceptually a number of authors have suggested that more decentralised sanitation systems are more flexible and hence reduce investment risk and adaptability to uncertainty (Spiller et al., 2015). This is reflected in the scores of the experts in this study. Therefore, in situations with large uncertainty opting for more decentralised systems can reduce investment risk and potential losses.

3.3.2.4 Social – the key barrier to implementation of novel sanitation systems

Social parameters are crucial for adoption of any sanitation system. If systems will not be accepted or cannot be operated adequately, the performance on all other parameters will be compromised. It is clear that there is a trade-off to be made between acceptance and competence requirements for operation and maintenance. Results indicated that systems that require less involvement of the individual, by demanding a higher level of competences, are thought to be more likely to be accepted, while simpler decentralised systems are less acceptable. The acceptance is related to the odor problems and simplification of the system for the users at household level. The present results clearly show that centralised systems (concept 4 and 5) are more accepted because of the low odor and robust systems for the users that tend to flush and forget. However, other studies on the opinion of real users indicated that new systems combining elements of source separation systems, local treatment and reduced water use are accepted by many end-users in the Netherlands and European countries (Lienert and Larsen, 2010, Poortvliet et al., 2018).

3.3.3 Contributions and limitations of the approach

The suggested approach in this study is generic to be applicable in different contexts under different considerations. Compared to the approach or software provided by Spuhler et al. (2020), this study provided simple steps that can be followed by decision-makers and urban planners to design a sustainable sanitation concepts considering different sustainability indicators. The approach can contribute to the existing theory that the assessment of sanitation concepts should be comprehensive, and able to assess different aspects contributing to the selection of a more sustainable sanitation concept. The quantification methods applied in this study can be generalized and applied in other similar contexts (Tropical regions). In confronting decision makers with the proposed structured stepwise process and a set of defined indicators, the choices will become more explicit and transparant. Thereby, it will also contribute to better decision, lasting implementation, and eventually an achievement of the SDGs (Haag et al., 2019). However, the suggested approach has some limitations that should be overcome through further study or development. The limitations is summarized as follows:

a. Selection of sanitation concepts
The approach applied in the case study focussed to only five sanitation concepts. The pre-selection of sanitation concepts for comparison should be done carefully considering local conditions and it should be supported through a literature review of possible technologies (Spuhler et al., 2020).

b. Selection of sustainable indicators
The selection of the indicators in this study is limited to the most cited indicators. However, in the implementation of the approach, it is possible to add other sustainability indicators considering the purpose of the sanitation concepts. The purpose of comparison should be pre-defined as it can influence the selection of the indicators.

c. Uncertainty of future developments
The suggested approach consider the uncertainty of the data. However, the uncertainty of future developments should be considered in the assessment of the performance of sanitation concepts. For example, future population development will influence the capacity of treatment technologies if it is not well-considered in the planning process.

3.4 Conclusion

- Conventional sewerage in combination with centralised anaerobic treatment and post treatment with a trickling filter is the best performing collection and treatment system, provided that the liquid effluent can be directly used for irrigation and fertilisation in agriculture. The key reasons for its superior performance can be found in comparatively low costs, land use and high energy production.
- The final ranking of sanitation concepts is sensitive to the selection of sustainability indicators and input variables.
- The approach allows the assessment of the whole train of technologies from collection, transport, treatment/recovery to reuse or final disposal, across the domains environmental, social-cultural, economic and technical. It can support urban planning and policy decision-making in selecting more sustainable sanitation concepts.

- In confronting decision makers with the proposed structured stepwise process and a set of defined indicators, sanitation system choices will become more explicit and transparent. Thereby, it will also contribute to better decisions, lasting implementation, and eventually an achievement of the SDGs.
- A major limitation of the studies is that the research does not account for uncertainty of future development which may affect the performance of wastewater treatment technologies. Such development maybe changes in the population, climate change or economic development. Future research should take this into account for example by developing explorative external scenarios.

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CHAPTER 4

An approach to evaluate the performance of sanitation systems under different future developments: A case study in St. Eustatius

I. Firmansyah[a], M. Spiller[b], F.J. de Ruijter[c], G. Zeeman[a,d], G.J. Carsjens[e]

[a] sub-department of Environmental Technology, Wageningen UR, Bornse Weilanden 9, 6708 WG, Wageningen, the Netherlands
[b]Research Group of Sustainable Energy, Air and Water Technology, Department of Bioscience Engineering, University of Antwerp, Groenenborgerlaan 171, 2020 Antwerpen, Belgium
[c]Wageningen University and Research, Agrosystems Research, P.O. Box 16, 6700 AA, Wageningen, The Netherlands
[d]Leaf BV P.O. Box 500, 6700 AM, Wageningen, the Netherlands
[e]Landscape Architecture and Spatial Planning Group, Wageningen UR, P.O. Box 47, 6700 AA, Wageningen, the Netherlands

To be submitted

Abstract

Several sanitation planning frameworks have been proposed to select sanitation technologies for an urban system. However, these frameworks do not include the uncertainty of future developments, such as the effect of climate and economic change. These future changes can influence the performance and selection of the sanitation systems. Therefore, this study develops an approach to evaluate the performance of sanitation systems under different future scenarios. External scenarios were applied to explore future development, and Multi-Criteria Decision Analysis (MCDA) was used to evaluate the performance of resource-orientated sanitation systems using sustainability indicators across different future scenarios. The approach was applied in St. Eustatius. In the context of St. Eustatius, centralised UASB (Upflow Anaerobic Sludge Bed) and Trickling Filter (TF) treating mixed black water and greywater have better performance in all future scenarios and reference situations compared to other concepts. The developed approach is not only suitable for St. Eustatius, but could also be applied to other similar situations and can be extended to larger systems. The approach can support planning and decision making for a more sustainable urban sanitation system.

Key words: scenarios, sanitation, resource recovery, domestic wastewater.

4.1 Introduction

During the last decades, the development of sanitation systems or concepts has increasingly focused on resource recovery and reuse (Vinnerås and Jönsson, 2002, Larsen et al., 2009, Zeeman, 2012). This development aims to transform the urban linear system into a circular system. Most urban systems have a linear metabolism where available resources are used once and subsequently disposed directly into the environment without being reused (Girardet, 1996). Within the concept of urban circular system, the disposed materials are recovered and reused for other purposes (Kennedy et al., 2011). This offers an approach to exploit alternative resources i.e. waste products through recovery and reuse. For example, nutrients are recovered from domestic waste and wastewater, and reused in agriculture (Agudelo-Vera et al., 2011). The concept of source separation is considered as a way to enhance the recovery and reuse of the resources (Kujawa-Roeleveld and Zeeman, 2006, Larsen et al., 2009). In sanitation systems involving source separation, domestic wastewater is separately collected, transported and treated as black water (BW: the mixture of urine, faeces, and flushing water), grey water (GW: laundry, shower, bath and kitchen water) and kitchen waste (KW).

Several frameworks have been developed to assist decision makers and planners to select domestic waste and wastewater treatment technologies and concepts (Loetscher and Keller, 2002, Hamouda et al., 2009, Larsen et al., 2010, Chamberlain et al., 2014, Garrido-Baserba et al., 2015, Zakaria et al., 2015, Kerstens et al., 2016). Loetscher and Keller (2002) proposed several steps to screen and select feasible technologies based on a range of criteria, such as settlement characteristics, soil characteristics, quality of water supply, community profiles and pollution control measures. Larsen et al. (2010) discussed how to select alternative sanitation concepts by looking at the process engineering objectives. Kerstens et al. (2016) developed an approach to select the technology based on a limited number of indicators, such as population density and urban functions. However, these sanitation planning frameworks do not consider uncertainty of future development, because the frameworks only focus on solving current sanitation problems of an urban system.

Planning and interventions concerning sanitation systems and resource recovery must deal with two types of uncertainties. Firstly, availability and variability of data must be considered as it is related to the validity of the assessments of the systems. For example, different literature sources report different removal efficiencies of sanitation technologies, which determine the performance of a sanitation technology. Secondly, future trends such as economic change can create different conditions of an urban wastewater system (van der Voorn et al., 2012; Van Vliet et al., 2010). For example, the size of the future population will influence the production of waste and wastewater. The amount of waste and wastewater might influence the selection of the sanitation technological concept to deal with these streams, and the performance of each concept will determine the final quality of the streams for discharge or reuse purposes. The two types of uncertainties and the resulting diverse future conditions will influence the potential applicability and effectiveness of sanitation concepts to recover resources, such as nutrients.

Scenarios have been applied to study the uncertainty of future circumstances (Börjeson et al., 2006, Höjer et al., 2008). Scenarios can depict the different futures that may arise due to various outcomes of development trends. Hence, scenario studies have been increasingly used to assist decision makers in making strategic decisions about long term perspectives for an uncertain future (Reed et al., 2009, Münster et al., 2013). However, little knowledge is available related to the use of scenarios concerning the implementation of sanitation concepts under different future developments. Kalbar et al. (2012) have studied the selection of appropriate wastewater treatment technologies based on scenarios that capture local and regional priorities related to the location of a treatment plant, the objective of treatment and land availability. However, the scenarios developed by Kalbar et al. (2012) did not include a systematic approach to explore external trends or drivers that can affect future developments of an area. Moreover, the study only considered the treatment technologies using conventional sewer systems and not the whole sanitation concept.

This paper presents an approach to evaluate the suitability and performance of different resource recovery and reuse orientated sanitation concepts under different future development scenarios to support environmental decision-making. Four external scenarios were developed to explore the uncertainties related to the future sanitation systems. The scenarios are based on an analysis of global and regional trends. The impact of the four external scenarios on the applicability of different sanitation concepts was evaluated using Multi Criteria Decision Approach (MCDA) including a set of sustainability indicators. The island of St. Eustatius in the Caribbean was used as a case study to develop the approach.

4.2 Methodology

4.2.1 Case study area: St. Eustatius

St. Eustatius, a small island located in the Caribbean region, had a total population of 3877 in 2015 and a total area of 2109 ha (Smith et al., 2013, Firmansyah et al., 2017). According to the Strategic Development Plan (SDP), St. Eustatius was expected to have an increase of population size and number of tourists (Hoogenboezem-Lanslots et al., 2010). However, the total population fluctuated over the years and decreased to 3138 in 2019 (CBS, 2019). Within the present study, the data of 2015 was used as a basis year and 2050 as projected year for developing and testing the approach.

Most of the agricultural products are imported to St. Eustatius because of the small area of agricultural land (6.8% of the total area), consisting of 3.6 ha arable land (horticulture) and 140.1 ha pastures (Smith et al., 2013). In 2015, all the wastewater produced in households was separately collected and treated with a simple technology. House-on-site soakage pits are the commonly applied technologies for blackwater treatment, and untreated greywater is discharged to the open ground or used for gardening. The solid household waste is collected and disposed directly into an open-dump landfill.

4.2.2 Approach

The approach developed in this study comprises five steps (Figure 4.1): (1) selection of sustainability indicators; (2) selection and assessment of sanitation concepts; (3) identification of future development trends; (4) development of external scenarios; and (5) assessment and ranking the performance of the selected sanitation concepts under different development scenarios. The developed approach aims to evaluate the impact of different future scenarios on the selection of sanitation concepts.

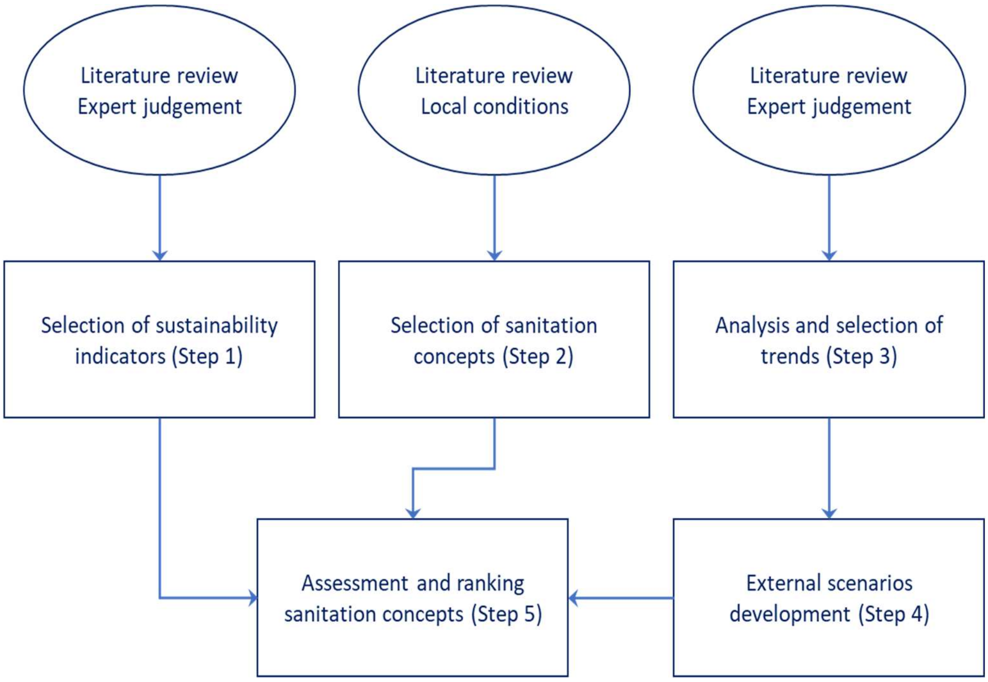

Figure 4.1 Approach for the assessment of sanitation systems performance under different future scenarios.

4.2.2.1 Selection of sustainability indicators (step 1)

Several sustainability indicators for wastewater technology assessment have been suggested in literature, ranging from environmental indicators (Balkema et al., 2002, Lundin and Morrison, 2002, Muga and Mihelcic, 2008), environmental and/or economic indicators (Hwang and Hanaki, 2000, Tsagarakis et al., 2003, Palme et al., 2005), and societal indicators. Based on a literature review, 12 key indicators were selected, covering four indicator categories: environmental, economic, social-cultural and technological. The indicators were chosen based on the most cited indicators for evaluating the performance of sanitation systems (Spiller, 2016). Detail information on the selected indicators can be seen in Firmansyah et al. (2021).

4.2.2.2 Selection of sanitation concepts (step 2)

The selection of sanitation concepts was based on a study by Firmansyah et al. (2021). In this study a variety of sanitation systems with multiple combinations of technologies across the process train of collection, transport, treatment, and disposal or reuse were reviewed to identify potential applicable sanitation systems for resource recovery and reuse (Zeeman et al., 2008, Massoud et al., 2009, Thibodeau et al., 2014, Tilley et al., 2014). In the study of Firmansyah et al. (2021), five sanitation concepts were selected for comparison based on discussions with sanitation experts and considering the local and regional conditions at St. Eustatius. The concepts differ in collection and transport systems, technologies for domestic wastewater treatment and the scale of operation. Treatment technologies such as Upflow Anaerobic Sludge Bed (UASB) and UASB-Septic Tank (UASB-ST) were selected for comparison, as UASB is a common domestic wastewater treatment applied in Latin America and Caribbean (LAC) (Giraldo et al., 2007), and UASB-ST is an improved version of the ST applied at household level (Kujawa-Roeleveld et al., 2005). GW at household level can be treated in a constructed wetland (CW) and reused for local irrigation/fertilisation. A Conventional Activated Sludge (CAS) system was included in the assessment as it is a commonly applied system for domestic wastewater treatment in industrialised countries (Zahid, 2007, RIONED, 2009). Small bore sewer systems and conventional gravity sewers are means to transport domestic wastewater (Mara and Guimarães, 1999). Composting facilities were included for combined treatment of KW and sludge produced during the treatment of domestic wastewater (Cofie et al., 2009).

4.2.2.3 Analysis and selection of trends (step 3)

Step 3 involved a trend analysis that aimed to identify potentially relevant trends that are long term and not under the control of the local decision makers. The year 2050 was selected as the target year for the trend analysis. Trends were considered relevant if they have an influence on the performance of sanitation concepts for resource recovery and reuse. Literature review and document study were used to support the selection of relevant trends and to collect data and information about their expected outcomes. The literature review and document study were primarily focused on identifying global and regional trends not in control of the local community at St. Eustatius. The identified trends were structured along the Social, Economic, Environmental, Political and Technological (SEEPT) framework (Krueger et al., 2001). The result of step 3 was a list of pre-selected trends with their expected range of outcomes, reflecting their future uncertainty.

4.2.2.4 External scenarios development (step 4)

The expected outcomes of the trends in the targeted year (2050) were used to build external scenarios. External scenarios are a category of explorative scenarios that aim to explore the long-term, future development of external trends that cannot be influenced by local decision makers, such as population development, economic development, and climate change (Börjeson et al., 2006, Münster et al., 2013).

The development of the external scenarios in step 4 started with the categorization of the identified trends, based on their level of impact and their uncertainty, using an impact-uncertainty matrix (Krueger et al., 2001). A "high-medium-low" rating system was used to distinguish between trends based on two factors: degree of uncertainty and level of impact (Figure 4.2). Supporting interviews and Focus Group Discussions (FGD) were conducted in February-March 2016 to discuss the relevance and potential impact of the pre-selected trends for St Eustatius and other neighbouring small islands. Six local stakeholders were interviewed, including representatives of the local government and non-governmental organisations (NGOs), and 16 stakeholders from different small islands in the Caribbean were invited to participate in the FGD (Supplementary Material (SM) section S3.1). The stakeholders represented island governmental agencies and NGOs of St. Eustatius and other small islands in the Caribbean. The interviews and FGD were carried out by means of semi-structured, open questions that allowed discussing the relevance and impact of each of the pre-selected trends on the development of St. Eustatius and other small islands in the Caribbean. The results from the interviews and FGD were used to categorize the trends for their impact and uncertainty.

Level of Impact / Degree of uncertainty	Low	Medium	High
High	**Critical planning issues** Highly relevant for sanitation planning and resource recovery and reuse and fairly predictable (based on existing projections). Taken into account in all scenarios.	**Important scenario drivers** Extremely important and fairly certain that can influence sanitation planning and resource recovery and reuse. Used to differentiate between scenarios.	**Critical scenario drivers** Factors and forces essential for resource recovery and reuse and highly unpredictable. Used to differentiate between scenarios.
Medium	**Important planning issues** Relevant for sanitation planning and resource recovery and reuse and very predictable. Should be figured into most scenarios.	**Important planning issues** Relevant for sanitation planning and resource recovery and reuse and somewhat predictable. Should be present in most scenarios.	**Important scenario drivers** Relevant issues that influence sanitation planning and resource recovery and reuse, and highly uncertain. Plausible, significant shifts in these forces should be used to differentiate between scenarios.
Low	**Monitorable issues** Related to the selection on sanitation concepts but not critical. Should be monitored for unexpected changes.	**Monitorable issues** Related but not crucial to the selection on sanitation concepts. Should be monitored for unexpected changes.	**Issues to monitor and reassess impact** Highly unpredictable forces that do not have an immediate impact on the selection on sanitation technologies. Should be closely monitored.

Figure 4.2 Impact/uncertainty matrix for sanitation planning and technologies for resource recovery and reuse (Adapted from Krueger et al., 2001)

The external scenarios were built around high-impact and high-uncertainty issues. Two trends with high uncertainty and high impact were selected as the scenario drivers. The diverging future outcomes of these two trends were used as the opposing ends of the two scenario axes, that framed the widest extent of possible future conditions the island of St Eustatius might be confronted with. Four differentiating scenarios were built around these axes, by aligning the outcomes of the other medium to high impact trends in this framework (Krueger et al., 2001) and building coherent scenario storylines.

4.2.2.5 Assessing and ranking sanitation concepts (step 5)

The assessment and ranking of the sanitation concepts considering future development included three parts:

1. quantification of the performance of sanitation concepts for each sustainability indicator, and normalisation of the indicator values to allow for mutual comparison.
2. assessment of the relative importance of the sustainability indicators from the perspective of each of the scenario storylines, indicated by a weight of 1, 2 or 3 (low, medium or high importance respectively).
3. multiplying the normalized indicator values and weights, using weighted sum model.
4. sensitivity analysis.

Ad 1. The quantification of the performance of the selected sanitation concepts for the context of St. Eustatius was based on the methodology described in Firmansyah et al. (2021). This included the assessment of the quantitative indicators, such as net energy use, nutrient recovery/reuse, BOD/COD, pathogens, GHG emission, capital expenditure (CAPEX), operational expenditure (OPEX) and the land area requirement. For the qualitative indicators, such as acceptance, required competences and education, institutional capacity, flexibility/adaptability and reliability, five sanitation experts were consulted. The experts were asked to assess each indicator using a five-point scale ranging from “bad” (1) to “good” performance (5). The results of the unweighted scores as presented in Firmansyah et al. (2021) were used as a reference to assess the performance of the selected sanitation concepts in future conditions.

The resulting values of quantitative and qualitative indicators were normalized using the technique of standardization or z-scores (Davis and Sampson, 1986). A z-score represents the distance between the value of an indicator and the mean for that indicator in units of the standard deviation (σ). A set of z-scores have a mean of 0 and a σ of 1. Consequently, a positive value (+) means that the value is above the mean, and a negative value (-) means that the value is below the mean (Equation 1).

$$r_{ij} = \frac{x_{ij} - \bar{x}_i}{\sigma_i}, \text{for } i = 1, \dots, m; j = 1, \dots, n \quad (1)$$

where r_{ij} is the z-score of indicator i for sanitation concept j, x_{ij} is the value of indicator i for sanitation concept j, $\bar{x}_i$ and σ_i are the mean and standard deviation of the values for indicator i respectively, and there are m indicators and n sanitation concepts. For most indicators, such as nutrient recovery/reuse and the qualitative indicators, a maximum value represents the best performance of a sanitation concept. For these indicators the z-score was calculated directly with Equation 3. However, for the indicators net energy use, BOD/COD in the effluent, pathogen in the effluent, GHG emission, land use, CAPEX and OPEX, minimum values represent the best performance. For those indicators the calculated z-scores were multiplied with -1, to make these comparable with the other indicators.

Ad 2. The relative importance of the sustainability indicators was expressed in weights, ranging from 1 to 3, where 1 represents a low importance and 3 a high importance. The weights were assigned by the authors in the context of each of the four external scenarios. For example, in a scenario with good economic growth, the economic indicators (CAPEX and OPEX) were assigned low weights, because of more budget becoming available, as compared to a scenario with low economic growth where the CAPEX and OPEX will be more important due to less budget being available. Likewise, the flexibility/adaptability and reliability/continuity of service were assigned higher weights in a scenario with severe climate change, where the sanitation systems have to face rapidly changing environmental conditions.

Ad 3. The final weighted scores of the sanitation concepts in each of the four scenarios was calculated by multiplying the normalized indicator values with their weights, using weighted sum model (Equation 2).

$$SC_j = \sum_{i=1}^{m} w_i r_{ij}, \text{for } i = 1, \dots, m \quad (2)$$

where SC_j is the total weighted score of sanitation concept j, w_i the weight of indicator i, r_{ij} the standardized z-score of indicator i for sanitation concept j, and m indicators.

Ad 4. In the sensitivity analysis the influence of the normalization technique and the range of weights on the final ranking of sanitation concepts were explored. In addition to the z-scores, we applied min-max normalization (Davis and Sampson, 1986), which is another common technique to normalize data (see Equation 3).

$$r_{ij} = \frac{x_{ij} - min_{ij}}{max_{ij} - min_{ij}}, \text{ for } i = 1, \dots, m; j = 1, \dots, n \quad (3)$$

where r_{ij} is the normalized score of indicator i for sanitation concept j, x_{ij} is the value of indicator i for sanitation concept j, min_{ij} and max_{ij} are the maximum and minimum values of the indicator values for sanitation concept j respectively, and there are m indicators and n sanitation concepts. Equation 3 is valid for indicators where a high value represents the best performance. However, for indicators where a low value represents the best performance (such as CAPEX and OPEX), the normalized values were calculated using 1 – Equation 3.

The influence of differences in weights on the final ranking was explored by expressing the weights in a different value range (1, 5, 10), thus enlarging the relative differences between the weights.

4.3 Results

4.3.1 Selection of sustainability indicators

The selected environmental indicators were energy use, nutrient recovery/reuse, Biochemical Oxygen Demand and Chemical Oxygen Demand (BOD) in the effluent, pathogens, greenhouse gas (GHG) emission, and land area requirement. The economic indicators included Capital Expenditures (CAPEX) and Operational Expenditures (OPEX). The social-cultural indicators were acceptance and required competences and education. The technological indicators comprised flexibility/adaptability and reliability/continuity of the service. These indicators were taken from Firmansyah et al. (2021), to enable a comparison with the outcomes of that study. Further details are provided in the SM S2.1.

4.3.2 Selection of sanitation concepts

The selected sanitation concepts for comparison are shown in Table 4.1. These concepts were taken from the Firmansyah et al (2021), to enable a comparison with the outcomes of that study.

Table 4.1 Sanitation concepts for comparison (Firmansyah et al., 2021)

Concept	Collection	BW transport and treatment	GW treatment	KW treatment	Recovered products[1]
1	BW and GW separately collected at household level. BW is collected with a flush toilet	ST at household level, BW effluent transported via small bore sewer system to a TF at community level	CW at household level	KW and BW sludge co composting	BW effluent, compost
2	BW and GW separately collected at household level. BW is collected with a flush toilet	UASB-ST at household level, BW effluent transported via small bore sewer system to a TF at community level	CW at household level	KW and BW sludge co composting	BW effluent, compost, energy
3	BW and GW separately collected at household level, BW is collected with a flush toilet	BW transported via a conventional sewer system to a UASB at community level followed by a TF	CW at household level	KW and BW sludge co composting,	BW effluent, compost, energy
4	BW and GW collected together. BW is collected with a flush toilet.	Mixed BW and GW transported via a conventional sewer to a UASB+TF at centralized level		KW and sludge co composting	BW and GW effluent, compost, energy

[1]Effluent and compost may be used in agriculture

4.3.3 Analysis and selection of trends

Recent trends and scenario studies, focusing on the Caribbean region, identified socio-economic developments, such as demographic shifts and economic progress as critical drivers for the future of the region (Marczak et al., 2016, Drakes et al., 2017). We gathered data about the generic, descriptive outcomes of these trends, instead of specific quantitative outcomes, which would have been too detailed for this study.

Social:
The use of water for domestic application is influenced by the number of people on the island. Therefore, demographic change will influence the amount of generated waste and wastewater on the island that will be the source for resource recovery and reuse (Wilsenach and Van Loosdrecht, 2003). Two trends were identified that represent demographic change at St Eustatius: change in the number of permanent residents (local population) and change in temporary residents (tourists and immigrant workers). In general, an increase in population is expected in the Caribbean region, but with slowing growth rates (Marczak et al., 2016, Drakes et al., 2017). The change in temporary residents in St Eustatius, especially related to the export-based and services type of jobs (Ecorys, 2010, Hoogenboezem-Lanslots et al., 2010), is more uncertain and will depend on the economic circumstances. Drakes et al (2017) expect these economic circumstances can differ from increasing GDP growth in the Caribbean on the one hand to stagnating or negative growth in GDP on the other. Accordingly, we assumed the total population change at St Eustatius will range from an increase in more favourable economic conditions to a stabilizing or declining total population in less favourable circumstances.

Economic:
Economic development is relevant as it determines the financial power to support the investment in and maintenance of sanitation infrastructure. Economic development can be assessed, for instance, from the value of the Gross Domestic Product (GDP) of a country or area. These are also related to the number of investments as a driver for the economic development on the island. As described above with the social trends, Drakes et al (2017) expect a future differentiation between a stagnating or negative GDP growth in the Caribbean on the one hand and an increasing GDP growth on the other.

Several reports indicate that the global fertilizer demand will increase (Alexandratos and Bruinsma, 2012). This is indicated by the increasing global food demand that requires more fertilizer and feed in future. Thus, it is expected that the fertilizer price will increase too, but the extent will depend on the availability of the included resources and the energy price. For the resource availability, it is expected that phosphorus, as one of the essential macronutrients in the fertilizer, might deplete in the coming 50-400 years (Cordell et al., 2009; Sattari et al., 2012; Smil, 2000). This condition is exacerbated as only a few countries (mainly Morocco, China and the US) have control of it, and thus might become a subject to international political influence (Cordell et al., 2009). Several pieces of evidence are mentioned in literature, such as the monopoly on Western Sahara's reserves, reduction of exports to secure domestic supply by China (Jasinski, 2005). Moreover, Nitrogen produced via the Haber Bosch process consumes around 1% worldwide energy use (Smith, 2002). The resources availability will influence future development related to the supply and the price of fertilizers on the world market. A more stable international situation and minor increase in energy price will result in a moderate increase in fertilizer price. A more unstable international situation and large increase in energy price will result in a strong increase in fertilizer price.

The trends of the global energy price will also influence the development and selection of sanitation concepts. A high energy prize might result in a focus on sanitation concepts that have an effective energy management. The energy price is driven by energy demand and supply (resource availability). A high energy demand, typically driven by more favourable economic conditions, will also influence the potential cost-savings of sanitation concepts producing energy that can be reused for other purposes. The International Energy Agency (IEA) reported in the World Energy Outlook 2017 that internationally energy prices will range from a minor/moderate increase to a major increase in the future depending on the energy demand and supply.

Environment:

Climate change influences the performance of sanitation concepts that eventually affects the selection of the technology for resource recovery and reuse. Precipitation will affect the amount and quality of treated wastewater as storm water can infiltrate into the treatment system depending on the location and design of the sanitation concept especially for open systems such as aerobic technological systems. Temperature is related to the evaporation process that can affect the amount of treated wastewater that can be recovered or reused. Moreover, under some conditions temperature influences the treatment process (Andersson et al., 2016). Sea level rise as a phenomenon that occurs due to climate change will affect the performance of sanitation concepts when a treatment plant is located in a coastal area. Hence, the climatic conditions will influence the selection of the technology that will be implemented for recovery and reuse. For example, some technologies perform well during high temperature such as anaerobic technologies for resource recovery and reuse, while land-based sanitation technologies, such as constructed wetland or pond systems, can have increased water evaporation at increased temperatures or reduced retention time due to strong precipitation.

Four different scenarios have been projected by the Intergovernmental Panel on Climate Change (IPCC) to assess the possible effects of climate change in the future (IPCC, 2014), the Representative Concentration Pathways (RCP) scenarios. In this research, the most extreme scenarios were used (RCP 2.6 and RCP 8.5) to capture the widest range of climate change effects in the Caribbean region. In the global RCP 2.6 scenario the annual average temperature increases with 0.5°C and the annual precipitation decreases with 10 mm, while in the RCP 8.5 scenario the temperature increases with 2.0°C and precipitation decreases with 30 mm in 2100. Although the average annual precipitation will decrease in both scenarios, extreme precipitation events are expected to become more intense and more frequent as result of increasing surface temperature every year (IPCC, 2014).

Political:
Enacting politically difficult but necessary reforms, such as promoting resource recovery and reuse, requires a strong governance capacity (Marczak and Engelke, 2016). It is expected that governance in Latin America and the Caribbean can move in two opposing directions. On the one hand towards strengthened democracies with strong governance and a minimal to moderate crime rate, and on the other hand towards an erosion of governance, leading to pervasive corruption, weakened rule of law, and crime and drug syndicates deeply embedded in society (Marczak and Engelke, 2016; Drakes et al., 2017). Strong governance can accelerate investment in sanitation development and effective wastewater management. This will allow for a more active and widespread information on circularity of resources and recovery and reuse technologies, resulting in high concern and awareness of the people. This eventually will contribute to a high quality of life. Contrary to this, the development of sanitation technology might not be a priority with a weak governance. This will slow down the transfer of technology (Drakes et al, 2017).

A summary of projected outcomes of the trends for St Eustatius in terms of low and high ends of development is shown in Table 4.2.

Table 4.2 Projected trends directions.

Trend	**Direction of development**	
	Low	**High**
Social		
1. Population development	Growth rates slow and falling; Low wastewater production	Growth rate increasing; High wastewater production
Economy		
2. Economic growth	Stagnant or negative GDP; no or little investment in sanitation technologies	Increasing GDP; high investment in sanitation technologies
3. Energy price	Moderate increase; low or little decision focus on the energy efficiency of sanitation technologies	Strong increase; high decision focus on the energy efficiency of sanitation technologies
4. Fertilizer price	Moderate increase; low or little decision focus on nutrient recovery by sanitation technologies	Strong increase; high decision focus on nutrient recovery by sanitation technologies
Environment		
5. Climate Change	Moderate climate change; less impact on (vulnerable) sanitation technologies	Severe climate change; more impact on (vulnerable) sanitation technologies
Politic		
6. Governance	Weak governance, high corruption and organised crime; little effectiveness of implementation and maintenance of sanitation concepts	Strong and community-oriented governance and minimal crime; high effectiveness of implementation and maintenance of sanitation concepts

4.3.4 External scenarios development

The six trends were classified for their uncertainty and their impact on the implementation and performance of the sanitation concepts (Figure 4.3). Three trends were classified as high uncertain/high impact (Population development, Economic Growth, Governance), one trend as medium uncertain/high impact (Fertilizer price), one trend as high uncertain/medium impact (Climate change), and one trend as medium uncertain/medium impact (Energy price).

Degree of uncertainty

Low	Medium	High	Degree of Impact
	Fertilizer price	Population development, Economic growth, Governance	High
	Energy price	Climate change	Medium
			Low

Figure 4.3 Classification of trends in the impact-uncertainty matrix.

Based on the trends in Figure 4.3, four plausible external scenarios were developed to explore the future of sanitation-agricultural systems of St. Eustatius in the year of 2050 (Figure 4.4). The two trends that were selected as the main axis scenario drivers were economic growth and governance in the Caribbean (Drakes et al., 2017). Economic development will strongly influence population growth and the demand for resources, such as food, water and energy, as well as waste(water) production. The governance situation will highly influence the effectiveness of implementation and maintenance of sanitation technology. The other trends were arranged in a coherent way in the resulting scenario axis (Figure 4.4). Each scenario is described in more detail in the form of a storyline below.

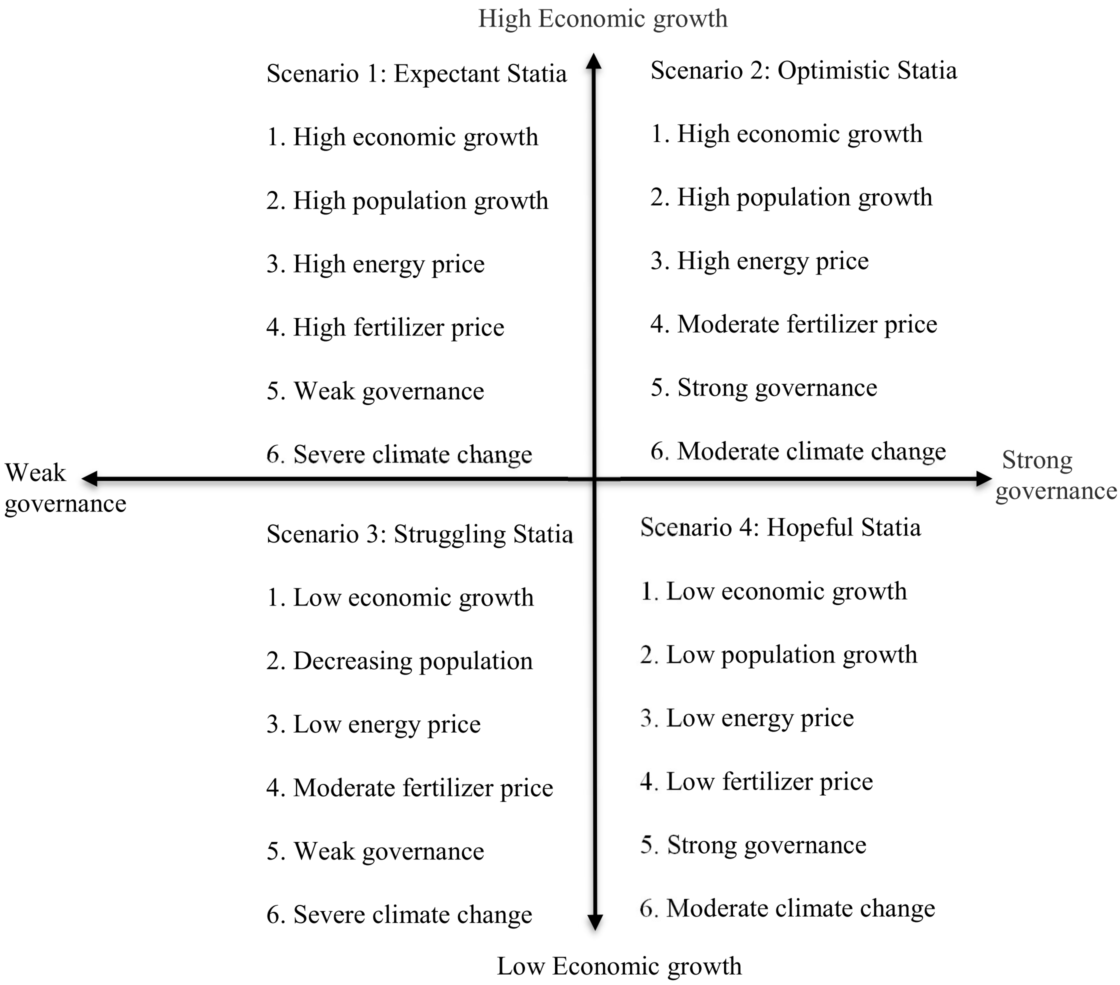

Figure 4.4 Four explorative external scenarios for St. Eustatius in 2050

Scenario 1: Expectant Statia depicts a situation with a high economic growth and a weak governance in the Caribbean and globally. Although new energy sources are adopted, the enforcement of the COP 21 agreement is weak, and industries still rely heavily on fossil fuel. The resulting climate change effects are severe. The high economic growth results in an increase of the tourism sector and oil terminal activities at St. Eustatius, and an increase of the number of people living on and immigrating to the island. As a result, a higher volume of wastewater is produced.

The global energy and fertilizer prices are high. However, the recovery of resources at the island is hindered by the weak governance and a lack of interest of people, who can afford a higher price of food.

Scenario 2: Optimistic Statia represents a situation with a high economic growth and strong governance in the Caribbean and globally. In this scenario, renewable energy and eco-friendly lifestyles are promoted. International organizations, such as the United Nations, function effectively. Due to the good enforcement of the COP 21 agreement, the climate change effects globally and on the island are moderate. Tourism and renewable energy development are the main focal points for economic development on St. Eustatius. The strong economy has resulted in an increase of population and a high production of wastewater. Due to a high global energy demand, the energy price is high, promoting the application of energy saving measures and the use of alternative energy on the island. This is supported by the strong and effective governance. Due to the high energy price, the fertilizer price has also increased, however, the strong global governance situation allows good access to nutrient reserves and resulted in a moderate growth of the fertilizer price. The strong governance and focus on climate change, as well as the strong economic situation, support efforts for resource recovery and reuse.

Scenario 3: Struggling Statia depicts a situation with a low economic growth and weak governance in the Caribbean region and globally. International organizations are weak, and countries are competing and struggling to maintain economic growth. Climate change is no longer a top priority on the international agenda, which results in severe climate change effects. At St. Eustatius, the low economic development results in stagnating tourism and oil terminal activities, which in turn result in a population decline on the island. However, due to the low economic growth globally the energy price is low too. Despite the low energy price, the weak governance situation restricts access to nutrient reserves, which results in a moderate growth of the fertilizer price. The weak economic situation and weak governance also hinder the investments in resource recovery and reuse.

Scenario 4: Hopeful Statia represents a situation where the Caribbean is confronted with a low economic growth and strong governance. Globally, there is a falling in a global trade. However, in the Caribbean this created momentum for regional integration and a stronger role of the government. The downfall of the global economies also resulted in a shift in environmental awareness, and economic models that support more sustainable paths and less climate change. Due to the global economic development, the tourism sector has stagnated. The oil terminal activities declined, in favour of renewable energy sources that enable the island to meet in its own energy demand. These new activities resulted in a minor population growth on the island. The low global economic growth resulted in a low energy price, which also reduced the fertilizer price. The strong local governance and focus on climate change supports investments in resources recovery and reuse, although these possibilities are limited due to the weak economic situation.

4.3.5 Assessing and ranking sanitation concepts

4.3.5.1 Quantification and normalization of indicator values

The quantified indicator values before standardizing were derived from Firmansyah et al. (2021). The indicator values were standardized using z-scores, which are shown in (Figure 4.5). Per indicator, the sum of the normalized values equals zero; positive values indicate a better-than-average performance, negative values a worse-than-average performance. Overall, Concept 4 has the highest performance and Concept 5 is the lowest.

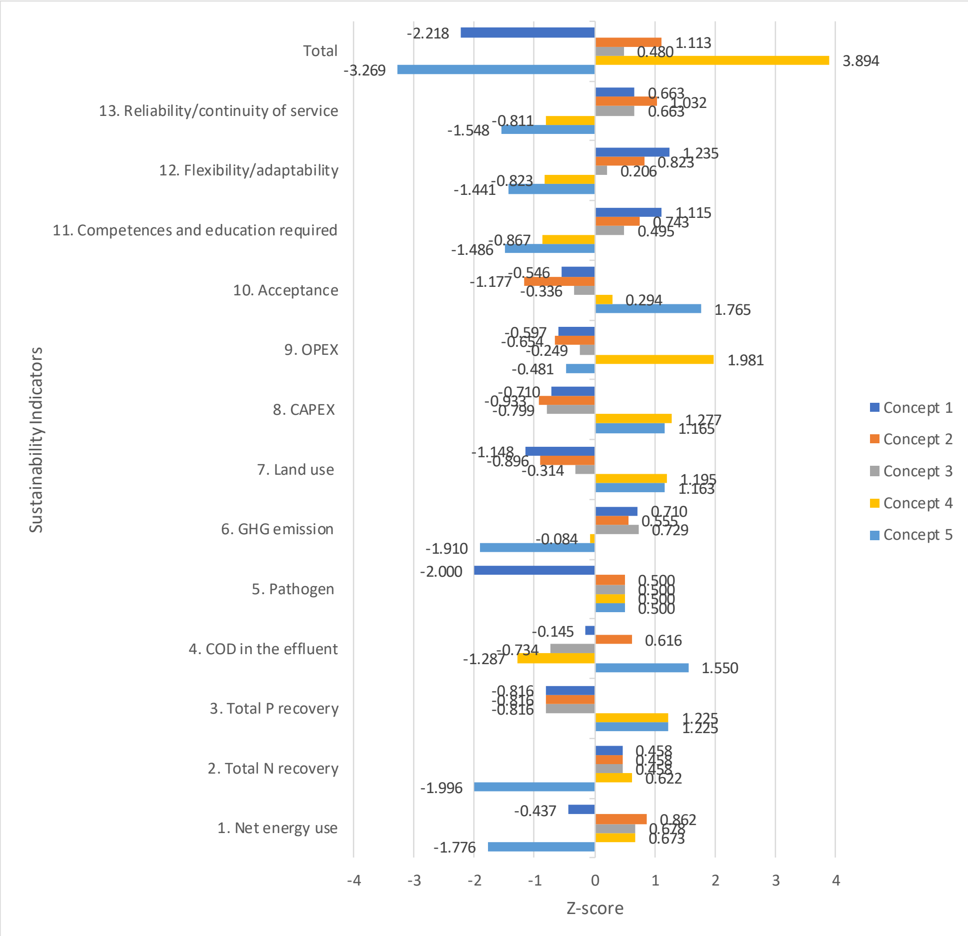

Figure 4.5 Normalized indicator values for performance of the five sanitation concepts

4.3.5.2 Assessment of the relative importance of indicators

The overview of the relative importance of the sustainability indicators for wastewater technology assessment in each external scenario is shown in Table 4.3. The rationale for assigning a low, medium or high importance to the indicators in each scenario is presented below.

Table 4.3 Relative importance (weight) of sustainability indicators per scenario, expressed as 1 (low), 2 (medium) or 3 (high)

Category	**Indicators**	**Scenarios**			
		Expectant Statia	**Optimistic Statia**	**Struggling Statia**	**Hopeful Statia**
Environ-mental	1. Net energy use	2	3	1	2
	2. Total N recovery	2	3	1	2
	3. Total P recovery	2	3	1	2
	4. COD in the effluent	2	3	1	2
	5. Pathogen	2	3	1	2
	6. GHG emission	2	3	1	2
	7. Land use	2	3	1	2
Economic	8. CAPEX	1	1	3	3
	9. OPEX	1	1	3	3
Socio-cultural	10. Acceptance	1	1	3	2
	11. Competences and education required	1	1	3	2
Techno-logical	12. Flexibility/adaptability	3	1	3	1
	13. Reliability/continuity of service	3	1	3	1

In *Expectant Statia*, the high energy and fertilizer prices and increasing population will result in more attention for energy saving and nutrient recovering technology. However, the weak governance and related lack of urgency to deal with environmental problems reduces the urgency to take measures. Therefore, the environmental indicators will have a moderate importance. The good economic situation will allow to invest in (more expensive) sanitation technology, and the economic indicators CAPEX and OPEX therefore have a low importance. The acceptance of new technology and the competences and education required will be of low importance, given the growing population and qualified work force in combination with the good economic situation. The flexibility/adaptability and reliability/continuity of service have a high importance due to the severe climate change in which the sanitation systems have to face rapidly changing environmental conditions and a weak governance which reduces effective interventions in these systems.

In *Optimistic Statia*, the high energy and fertilizer prices will result in more attention for energy saving and nutrient recovering technology. The increase in population and the strong governance situation and related urgency to deal with environmental problems further increases the urgency to take measures. Therefore, the environmental indicators will have a high importance. The good economic situation will allow to invest in (more expensive) sanitation technology easily, and the economic indicators CAPEX and OPEX therefore have a low importance. The acceptance of new technology and the competences and education required will be of low importance, given the growing population and qualified work force in combination with the good economic situation. The flexibility/adaptability and reliability/continuity of service have a low importance due to the moderate climate change in which the sanitation systems face more stable environmental conditions and a strong governance which supports effective interventions in these systems.

In *Struggling Statia*, the low energy and fertilizer prices will result in a minor attention for energy saving and nutrient recovering technology. The declining population and weak governance and related lack of urgency to deal with environmental problems reduces the urgency to take measures even further. Therefore, the environmental indicators will have a low importance. The bad economic situation will not allow to invest in (more expensive) sanitation technology easily, and the economic indicators CAPEX and OPEX therefore have a high importance. The acceptance of new technology and the competences and education required will be of high importance, given the declining population and qualified work force in combination with the bad economic situation. The flexibility/adaptability and reliability/continuity of service have a high importance due to the severe climate change in which the sanitation systems have to face rapidly changing environmental conditions and a weak governance which reduces effective interventions in these systems.

In *Hopeful Statia*, the low energy and fertilizer prices will result in a minor attention for energy saving and nutrient recovering technology. However, the minor increase in population and the strong governance situation and mind shift to deal with environmental problems does support the urgency to take measures. Therefore, the environmental indicators will have a moderate importance. The bad economic situation will not allow to invest in (more expensive) sanitation technology, and the economic indicators CAPEX and OPEX therefore have a high importance. The acceptance of new technology and the competences and education required will be of moderate importance. Although there is a minor growth of population and qualified work force as compared to the Struggling Statia scenario, the equally bad economic situation makes investing in training difficult. The flexibility/adaptability and reliability/continuity of service have a low importance due to the moderate climate change in which the sanitation systems face more stable environmental conditions and a strong governance which supports effective interventions in these systems.

4.3.5.3 Ranking sanitation concepts

Table 4.4 shows the final ranking of sanitation concepts per scenario after multiplying the scores and weights for each indicator and calculating the total weighted scores for each sanitation concept. The values of the reference situation represent the sum of unweighted values. The detailed results are presented in SM section S3.2.

Table 4.4 Final total (weighted) scores and ranks of sanitation concepts; the cells are colored if the rank is different from the unweighted (reference) situation

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Reference	-2.218	1.113	0.480	3.894	-3.269
rank	4	2	3	1	5
Scenario 1	-6.127	2.627	1.194	7.586	-5.280
rank	5	2	3	1	4
Scenario 2	-8.099	3.597	0.511	9.744	-5.752
rank	5	2	3	1	4
Scenario 3	-0.773	0.855	1.410	5.830	-7.323
rank	4	3	2	1	5
Scenario 4	-5.095	0.259	0.026	9.678	-4.868
rank	5	2	3	1	4

The results show that in all scenarios and in the reference situation, Concept 4 (UASB+TF at centralized level) is ranked the best. It can be concluded that the concept is robust in the context of the four scenarios for St. Eustatius. The ranking of the concepts is equal in scenarios 1, 2 and 4. In these scenarios, Concept 2 is second, Concept 3 is third, Concept 5 is fourth, and Concept 1 ranks lowest. However, in scenario 3 (Struggling Statia) the order differs and Concept 3 is second, 2 is the third, concept 1 is the fourth, and concept 5 is the fifth. Concluding, Table 4.4 shows that Concept 4 (UASB+TF at centralized level) has the best overall performance in all scenarios. The application of UASB at household and community level is the second-best option, where Concept 2 at household level performs better in three of the four scenarios, and Concept 3 in one scenario. The application of ST+TF and CAS show the least overall performance.

Two opposing scenarios, 2 (Optimistic Statia) and 3 (Struggling Statia), were analysed in more detail along the weighted totals of the different indicators (Figures 4.6 and 4.7).

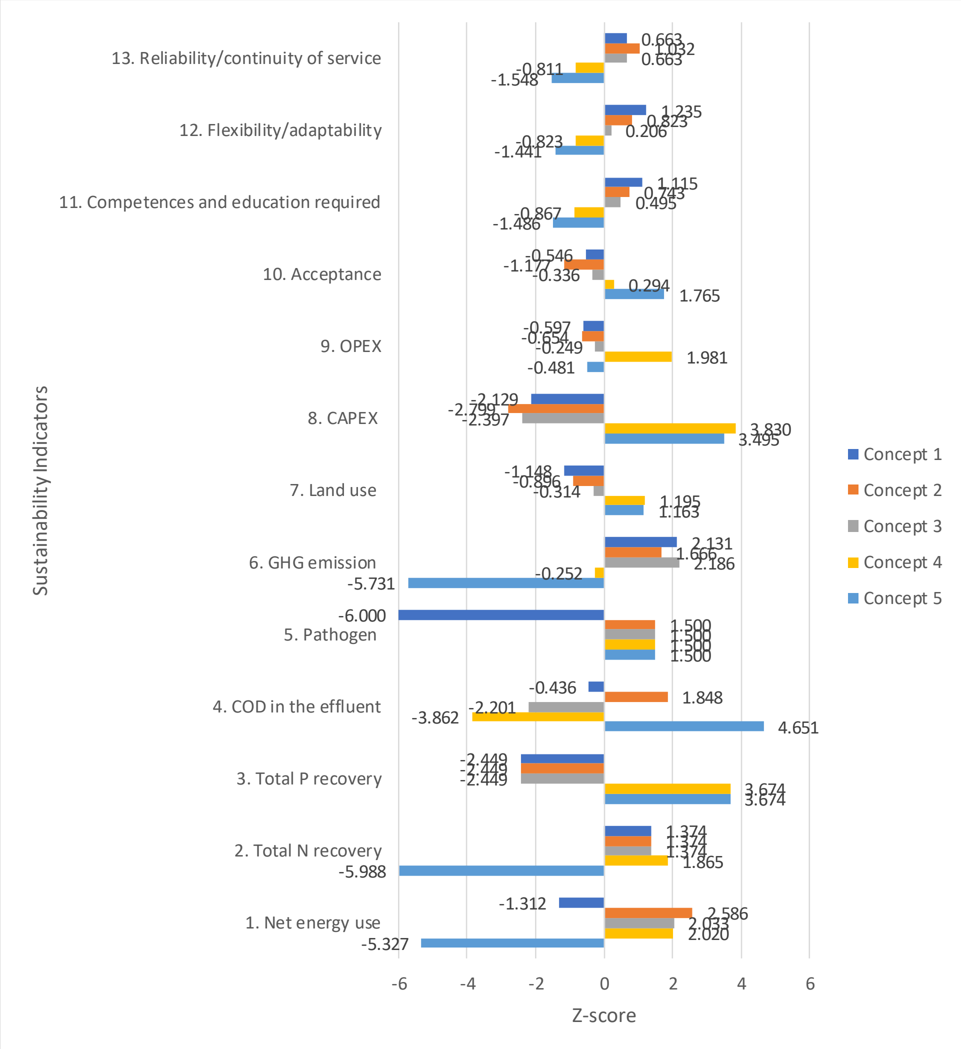

Figure 4.6 Weighted totals of the 13 indicators per concept of Scenario 2: Optimistic Statia

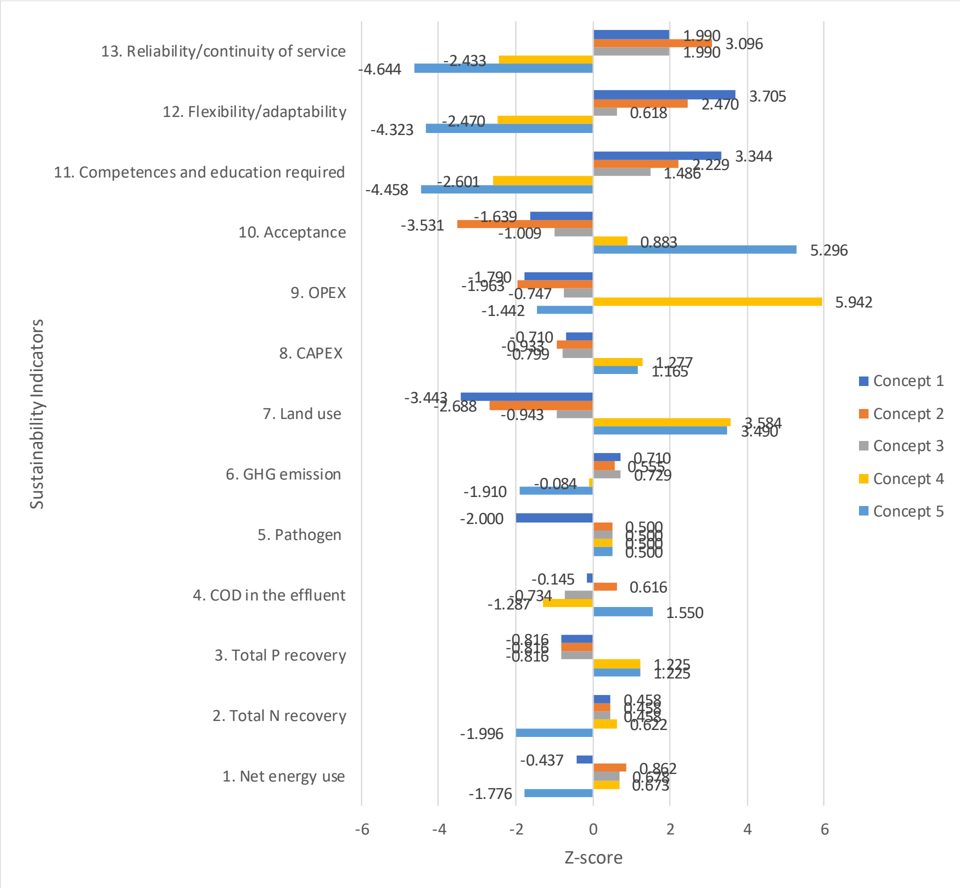

Figure 4.7 Weighted totals of the 13 indicators per concept of Scenario 3: Struggling Statia

The differences in the scores of the indicators between Figures 4.6 and 4.7 are caused by the differences in weights. In Figure 4.6 the environmental indicators (indicators 1 to 7) are expressed at a much larger value range as compared to Figure 4.7, due to the high weight of these indicators in scenario 2 (weight 3) and the low weight in scenario 3 (weight 1). The opposite is true for the economic (8 and 9), socio-cultural (10 and 11) and technological (12 and 13) indicators, with a weight of 1 in scenario 2 and a weight of 3 in scenario 3. Despite these apparent differences, concept 4 still gained the highest rank in all scenarios, as explained with Table 4.4.

Looking in more detail at the differences in weighted scores between the five concepts we can conclude that concept 4 especially performs well on the nutrient recovery indicators (N and P), land use (indicator 7) and the two economic indicators (OPEX and CAPEX). Concept 4 performs the least on the indicators 4 (COD) and 13 (reliability/continuity of service).

4.3.5.3 Sensitivity analysis

In the first part of the sensitivity analysis we analyzed the effect of using the min-max normalization technique instead of z-scores. The normalized scores using min-max are shown in Table 4.5.

Table 4.5 Normalized indicator values for the five sanitation concepts using the min-max normalization technique

Category	**Indicators**	Concepts				
		1	2	3	4	5
Environmental	1. Net energy use	0.507	1.000	0.930	0.928	0.000
	2. Total N recovery	0.938	0.938	0.938	1.000	0.000
	3. Total P recovery	0.000	0.000	0.000	1.000	1.000
	4. COD in the effluent	0.402	0.671	0.195	0.000	1.000
	5. Pathogen	0.000	1.000	1.000	1.000	1.000
	6. GHG emission	0.993	0.934	1.000	0.692	0.000
	7. Land use	0.000	0.107	0.356	1.000	0.987
Economic	8. CAPEX	0.101	0.000	0.061	1.000	0.949
	9. OPEX	0.022	0.000	0.154	1.000	0.066
Social-Cultural	10. Acceptance	0.214	0.000	0.286	0.500	1.000
	11. Competences and education required	1.000	0.857	0.762	0.238	0.000
Technological	12. Flexibility/adaptability	1.000	0.846	0.615	0.231	0.000
	13. Reliability/continuity of service	0.857	1.000	0.857	0.286	0.000
	Total	6.035	7.353	7.153	8.875	6.002

Although the normalized values are expressed at a different range, the resulting ranking after calculating the total weighted scores remained the same as with the z-scores for all scenarios. From this analysis we can conclude that the final ranking of sanitation concepts is not sensitive to changes in the normalization technique.

The second part of the sensitivity analysis included the use of a different set of weights (1, 5, 10). The results of applying these weights are shown in Table 4.6.

Table 4.6 Final total (weighted) scores and ranks of sanitation concepts using the adapted (1, 5, 10) scale of weights; the coloured cells show the differences between the ranks of the weighted scores using the 1-3 and the 1-10 scales

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Reference	-2.218	1.113	0.480	3.894	-3.269
rank	4	2	3	1	5
Scenario 1	-18.3378	7.304115	3.682755	19.04904	-11.6981
rank	5	2	3	1	4
Scenario 2	-28.6832	12.28945	0.617363	30.21972	-14.4433
rank	5	2	3	1	4
Scenario 3	4.285258	-0.04724	4.665211	12.60953	-21.5128
rank	3	4	2	1	5
Scenario 4	-14.868	-4.13601	-1.92154	29.30657	-8.38103
rank	5	3	2	1	4

The results show some similarities with that of the 1-3 scale. Concept 4 remains the best across all the scenarios, and the ranking of the concepts remains similar in scenarios 1 and 2. Some differences appear in scenarios 3 and 4, where the ranking is different. In scenario 3 concept 1 now performs better than concept 2, and in scenario 4 concept 3 performs better than concept 2. This changes the overall conclusion a bit, as concept 3 is now performing slightly better as second-best option compared to concept 2. However, there is no big difference in results between the 1-3 and 1-10 scales. Therefore, the final ranking seems quite insensitive for changes in weights, making concept 4 a robust sanitation concept in different future conditions.

Finally, we also analysed the effect of combining the 1-10 scale with the min-max technique, but this gave exactly the same results as the 1-10 scale with the z-scores, confirming that the choice between these normalization techniques does not influence the final ranking.

4.4 Discussion

The development of the presented approach enables selecting the best-performing sanitation concepts under different future circumstances in the context of a small tropical island. The approach builds on an approach presented by Firmansyah et al. (2017), adding development trends and external scenarios to assign weights to the sustainability indicators and using weighted-sum models to calculate total weighted scores. Compared with other approaches in sanitation planning (Kerstens et al., 2016, Spuhler et al., 2020), this approach provides a more holistic planning perspective that better integrates aspects of sanitation technological planning with uncertainties of future development. The approach uses development trends and external scenarios to explore the impacts of future uncertainties on the performance and selection of sanitation concepts. This has never been done in the field of sanitation technology and management before. In a research conducted by Kalbar et al. (2012) a scenario for the assessment of the performance of sanitation concepts was used. However, this scenario was limited to local conditions, only covering the location of a treatment plant, the objective of treatment, and the land availability for the selection of sanitation technologies (Kalbar et al., 2012), not including a systematic approach to explore external trends or drivers that can affect the future developments of an area. Moreover, the technological selection did not consider whole sanitation concepts consisting of collection, transport, and treatment/recovery technologies. In fact, the presented approach is the first attempt to apply external scenarios in the context of sanitation technological systems for recovery and reuse.

The results show no variation in the best-performing concept (centralized UASB+TF) between the scenarios and the reference situation. This indicates that the concept will be a robust choice for St Eustatius in different future conditions. However, this research involves a singular case only, and further explorations are needed in the context of other study areas to gain broader data about the performance of sanitation concepts in other contexts. For example, in low/medium temperature climates no crops will grow during wintertime and therefore nutrients cannot be applied. These conditions can affect the selection of sanitation concepts. Additional cases will also allow to further test and validate the approach for identifying the best-performing sanitation concepts.

Potential weaknesses of the approach are its relative complexity and the required resources in terms of access to literature, data, time, knowledge and funding. The complexity makes it less suitable for a participatory planning process, where the approach will easily become a black box to participants. The issue of complexity has been widely studied in planning support systems literature (Geertman and Stillwell, 2004, Carsjens and Ligtenberg, 2007, Vonk et al., 2007). Geertman and Stillwell (2004) argue that more complex tools are more suitable in a traditional planning process with planning professionals making use of the tool.

Further research can explore several methodological aspects of the approach. The use of external scenarios makes it possible to assess the performance of sanitation concepts in a range of future conditions. However, the use of scenarios also implies that the future can be predicted to a certain extent by extrapolating trends. Since the current societal and environmental context is becoming increasingly complex and unpredictable, the use of additional techniques might be required, such as exploring unforeseen or disruptive events using weak signals or wild cards (Dammers et al., 2014, Takala and Heino, 2017). For example, the global pandemic of Covid-19 has influenced different aspects of life that has to be taken into account for the planning and implementation of sanitation concepts.

The aspect of timing in assigning values to the assessment criteria is another aspect for further exploration, especially in the context of changing economic and other conditions (Payet-Burin et al., 2019). For example, the timing of capital costs (CAPEX) will be linked more to current and near-future economic conditions, while operational costs (OPEX) are linked more to long-term economic conditions.

Finally, in the current approach we used the simple multi-criteria technique of Weighted Sum Model. Other multi-criteria techniques can be applied, such as Analytic Hierarchy Process (AHP) (Bao et al., 2016), or Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Wolman et al., 2018). These techniques or methods have the same objectives to select best performing sanitation technologies or concepts across different criteria or indicators.

4.5 Conclusions

The approach developed in this study is considered as a step to explore future development of a small tropical island with regard to the selection of sanitation concepts promoting resource recovery and reuse. It allows for the identification of potential sanitation concepts to recover energy and nutrients from domestic waste and wastewater. The nutrients can be reused in agriculture under different future scenarios. Moreover, based on the context, different weights to the sustainability indicators can be assigned to cover for management preferences or expected developments. Applying this approach will result in the evaluation of a more reliable sanitation system that can perform better under specific future development. Planners can, therefore, use this approach to make decisions about future interventions for a transition for closing nutrient cycles in urban-agricultural system. However, there are some limitations related to the application of the approach. The complexity of the method or approach can hinder its application. This can be compensated with the involvement of experts or professionals that can advise for better planning for the future. Results of this study indicated that it is plausible to assess different sanitation concepts under different scenario development. It shows that the application of concept 4 is a robust concept in the context of St. Eustatius considering different aspects of future development.

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CHAPTER 5

Effect of domestic waste and wastewater reuse in agriculture on nutrient flows of a small tropical island

I. Firmansyah[a], M. Spiller[b], G.J. Carsjens[c], G. Zeeman[a,d], F.J. de Ruijter[e]

[a]Wageningen University & Research, Sub-department of Environmental Technology, Bornse Weilanden 9, 6708 WG, Wageningen, the Netherlands
[b]Research Group of Sustainable Energy, Air and Water Technology, Department of Bioscience Engineering, University of Antwerp, Groenenborgerlaan 171, 2020 Antwerpen, Belgium
[c]Wageningen University & Research, Landscape Architecture and Spatial Planning Group, P.O. Box 47, 6700 AA, Wageningen, the Netherlands
[d]Leaf BV P.O. Box 500, 6700 AM, Wageningen, the Netherlands
[e]Wageningen University & Research, Agrosystems Research, P.O. Box 616, 6700 AP, Wageningen, the Netherlands

To be submitted

Abstract
The concept of reusing N and P to achieve self-sufficiency in food production and to reduce emissions to the environment can be of paramount importance for small tropical islands as these islands rely on imported food and fertilizers. To achieve this, a better understanding of the nutrient flows on these islands and the effect of reuse on nutrient flows is required. Previous studies have assessed the performance of sanitation concepts for recovering nutrients, but these studies did not assess the effects of nutrient recovery and reuse on agriculture and nutrient flows in a small tropical island context. This paper aims to assess the effect of nutrient recovery from domestic waste and wastewater on agricultural production and the nutrient flows at the island of St Eustatius, using a Substance Flow Analysis (SFA) approach. The application of Upflow Anaerobic Sludge Bed plus Trickling Filter reactors (UASB+TF) and a composting system were selected to analyse the recovery of nutrients from respectively domestic wastewater and market waste, kitchen waste plus produced sludge. A model was used consisting of nine sub-systems: agricultural and natural lands, crop production, animal production, market, household consumption, open-dump landfill, sanitation concept (UASB+TF), composting, and urban lands. The effective use in agriculture was discussed for aspects such as handling/transportability, storage, health and safety of the products. The results showed that reuse of recovered nutrients in agriculture required an increase in agricultural area, and that nutrient flows on the island were strongly affected. The island could become independent of external nutrient inputs in the form of fertiliser, increase the local agricultural production, and reduce the amount of imported food, and reduce N losses to the environment by 4%. In conclusion, this study allows for better understanding of the nutrient flows and for improving nutrient management in a small tropical island context.

Key words: nutrients, sanitation, waste, wastewater, recovery and reuse, agriculture, small tropical islands.

5.1 Introduction

In recent years, waste(water) has been studied for its potential use in agriculture across the world as it contains water and nutrients that can be recovered and reused (Sharma and Sanghi, 2013). Roughly, two categories of products for use in agriculture can be distinguished: liquid and solid products. Examples of liquid products are treated wastewater (effluent) containing nutrients (Huibers and Van Lier, 2005) and separately collected and treated urine (Jönsson et al., 2004). Solid products can be compost (Vinnerås, 2007), sludge (Campbell, 2000), sewage sludge ash (SSA) (Adam et al., 2009), ammonium salts (Bisschops et al., 2019) and struvite (Cordell et al., 2011, de Graaff et al., 2011, Rahman et al., 2014). These nutrient-containing products originating from human waste(water) streams can substitute chemical fertilizers and thereby reduce the use of phosphate rock for phosphorus (P) fertilizer and reduce the use of fossil fuel to produce nitrogen (N) fertilizer (Mehta et al., 2015). Production of chemical N-fertilizer is an energy intensive process (37-45 kJ per Kg N fertilizer) and uses methane to produce the NH_3 (Maurer et al., 2003). For P, which is an essential macro nutrient, circular use is needed as the reserves of phosphate rock for fertilizer production are estimated to be exhausted in the next 100 to 400 years (Driver et al., 1999, Cordell et al., 2009).

Two basic concepts for recovering nutrients for potential reuse in agriculture can be distinguished: 1) recovery of water and nutrients from municipal or domestic wastewater that is collected and treated in a (de)centralised system (Lee et al., 2013), and 2) recovery from source separated sanitation or new sanitation (Zeeman, 2012), where Black Water (BW, the mixture of urine, faeces, cleansing material, and flushing water) and Grey Water (GW, laundry, shower, bath and kitchen water) are treated separately. BW has a relatively low volume and high nutrient content (it contains about 90% of the N and 77% of the P from household waste) and is a source for recovery and use as fertiliser, while GW contains few nutrients and can be a source for water reuse (Kujawa-Roeleveld and Zeeman, 2006).

Mixed BW and GW has been applied as a source of irrigation water that also contains nutrients to fertilize crops (Jaramillo and Restrepo, 2017). Sludge or biosolids, is a by-product from the treatment of domestic wastewater on-site (e.g. septic tank) and off-site (e.g. conventional activated sludge, UASB) systems. Sludge is a solid-based product that is rich in nutrients and organic matter and can be reused in agriculture. Because of health and safety requirements, the sludge requires treatment before use to reduce pathogens. One option is co-composting the sludge with other organic waste streams to produce compost (Cofie et al., 2009).

Small islands often depend on food and fertilizer import for their domestic needs (Saint Ville et al., 2015), whereas they also can have issues with nutrient loss due to lack of sufficient domestic waste and wastewater management (Firmansyah et al., 2017). Therefore, the concept of reusing N and P to achieve self-sufficiency in food production and to reduce emissions to the environment can be of paramount importance for small islands (Douglas, 2006, Forster et al., 2011). To achieve this, a better understanding of the nutrient flows on these islands and the effect of the reuse on nutrient flows is required. A suitable context for such a study is a small tropical island, with a clearly delineated area and a continuous crop system.

Firmansyah et al. (2017) have studied nutrient flows across urban and agricultural systems in the small island context of St. Eustatius. While this study assessed nutrient flows, it did not elaborate on sanitation concepts and use of recovered products in agriculture to couple urban and agricultural systems. Firmansyah et al. (2021) compared different sanitation concepts to assess their performance in nutrient recovery for potential reuse in agriculture (Firmansyah et al., 2021). The study was extended to compare the performance of sanitation concepts under different future scenarios (Chapter 4). The reuse of recovered nutrients in agriculture for food production and the influences on the nutrient flows on the island were not elaborated in these studies. Therefore, the objective of this study is to assess the effect of linking nutrient recovery by the best performing sanitation concept from the previous study with agricultural production in a small tropical island context. The island of St. Eustatius in the Caribbean was used as a case study.

5.2 Methodology

5.2.1 Description of study area

St. Eustatius is a small island located in the Caribbean, with a total population of 3877 in 2015 and an average number of 2.0 people per household (CBS, 2015). The total area is 2109 ha and the total urban area is 191 ha, in which houses are scattered on the island in approximately five neighbourhood areas (Smith et al., 2013, Firmansyah et al., 2017). Soakage pits are the commonly applied technology for BW treatment, and untreated GW is discharged to the open ground or used for gardening. The solid household waste is collected and disposed directly into an open-dump landfill (Firmansyah et al., 2017). This practice causes environmental pollution as untreated wastewater and organic waste emit nutrients and greenhouse gases (GHG) that contribute to environmental pollution (Firmansyah et al., 2017). It has been estimated that in St. Eustatius the volume of generated blackwater is equal to 34 L/p/day and greywater is 11.7 L/cap/day (Ghisi and Ferreira, 2007).

5.2.2 Selected sanitation concept

The sanitation concept selected in this study is based on the results of Firmansyah et al. (2021) and Firmansyah et al. (Chapter 4). The best technology that performs well under different future conditions, considering different sustainability indicators, is the application of Upflow Anaerobic Sludge Bed Reactor (UASB) treating mixed BW and GW at island level, and using Trickling Filter (TF) as post-treatment of anaerobically treated effluent. This technological concept has been widely applied for (de)centralized sewage treatment in Latin America and Caribbean Countries (LAC) (Noyola et al., 2012). For post-treatment of anaerobically treated effluent, a trickling filter (TF) was selected as the most commonly applied technology in LAC countries, e.g in Brazil (Bressani-Ribeiro et al., 2018, Noyola et al., 2012). The sludge from the UASB is further processed by co-composting with kitchen waste to produce compost. The addition of KW provides sufficient biodegradable carbon to enable increase of the process temperature to a level that pathogens are sufficiently decayed to allow for safe use of the produced compost in agriculture (Strauss et al., 2003, Koné et al., 2007, Oarga Mulec et al., 2016). Whilst, the treated effluent can be used in agriculture as liquid fertilizer/irrigation water.

5.2.3 Nutrient recovery by the selected sanitation system

The amount of nutrients recovered by applying UASB and TF was calculated based on the removal efficiencies and emissions of the treatment technologies that determine the fraction of nutrients ending up in the liquid, solid products, or those dissipating to the environment (i.e. for N only).

The combination of the UASB and the TF treating blackwater and greywater remove 27% for TN and 5% for TP from the liquid (Firmansyah et al., 2021). The treated effluent containing nutrients is subject for reuse in agriculture. The sludge contains 25.4% of the total influent N (the other 1.6% is emitted in gaseous form) and 5% of the total influent P. The sludge is co-composted with kitchen waste and market waste. The nutrient content of the final product (compost) was calculated, taking into account emissions to the atmosphere and leaching to the environment (See Supplementary Material (SM) Table S4.1).

5.2.4 Treated products and their application as fertilizer

In this study, the recovered products from treatment of wastewater and kitchen waste can be categorised based on their water content as stipulated in Table 5.1.

Table 5.1 Type of products derived from domestic waste(water) treatment

Product category	Origin	Products
Liquid	Mixed blackwater and greywater	Treated effluent
Solid	Mixed blackwater and greywater, kitchen waste, market waste	Compost

Storage, transport and field application differ between both product categories. Compost can be piled, transported and spread over fields. For the treated effluent, a storage tank or pond is needed as buffer between production and reuse and to prevent over-fertilization or -irrigation. The treated effluent can be applied in agricultural land using drip irrigation methods or can be used in hydroponic systems (Tabatabaei et al., 2020).

5.2.5 Substance Flow Analysis (SFA)

Substance Flow Analysis (SFA) was applied as the main methodology to model the effect of resource recovery and reuse on nutrient flows on a small island (Bringezu et al., 2009). The geographical land border of St. Eustatius (terrestrial region) was applied as the system boundary of the present study. The SFA approach as developed by Firmansyah et al. (2017) was applied as a basis and adjusted for the purpose of the present study to compare the baseline conditions (Figure 5.1) with future conditions (Figure 5.2). Under future conditions the application of the selected sanitation concept for nutrient recovery and reuse in agriculture is prevailing. In the SFA, nine sub-systems were defined with stocks, input and output flows. These sub-systems are agricultural and natural lands, urban lands, crop production, animal production, market, household consumption, UASB and TF, composting, and open-dump landfill. Twenty nine flows containing N and P through the sub-systems and its quantification methods were identified. Data sources and quantification per sub-system of the future conditions can be found in the Supplementary material (Table S4.1). To determine the effect of applying the selected treatment system and reuse of recovered nutrients and water in agriculture, calculations for both baseline and new system were based on the same reference year data (2013). STAN software version 2.5 (Cencic and Rechberger, 2008) was used for consideration of uncertainties, data reconciliation, and visualisation.

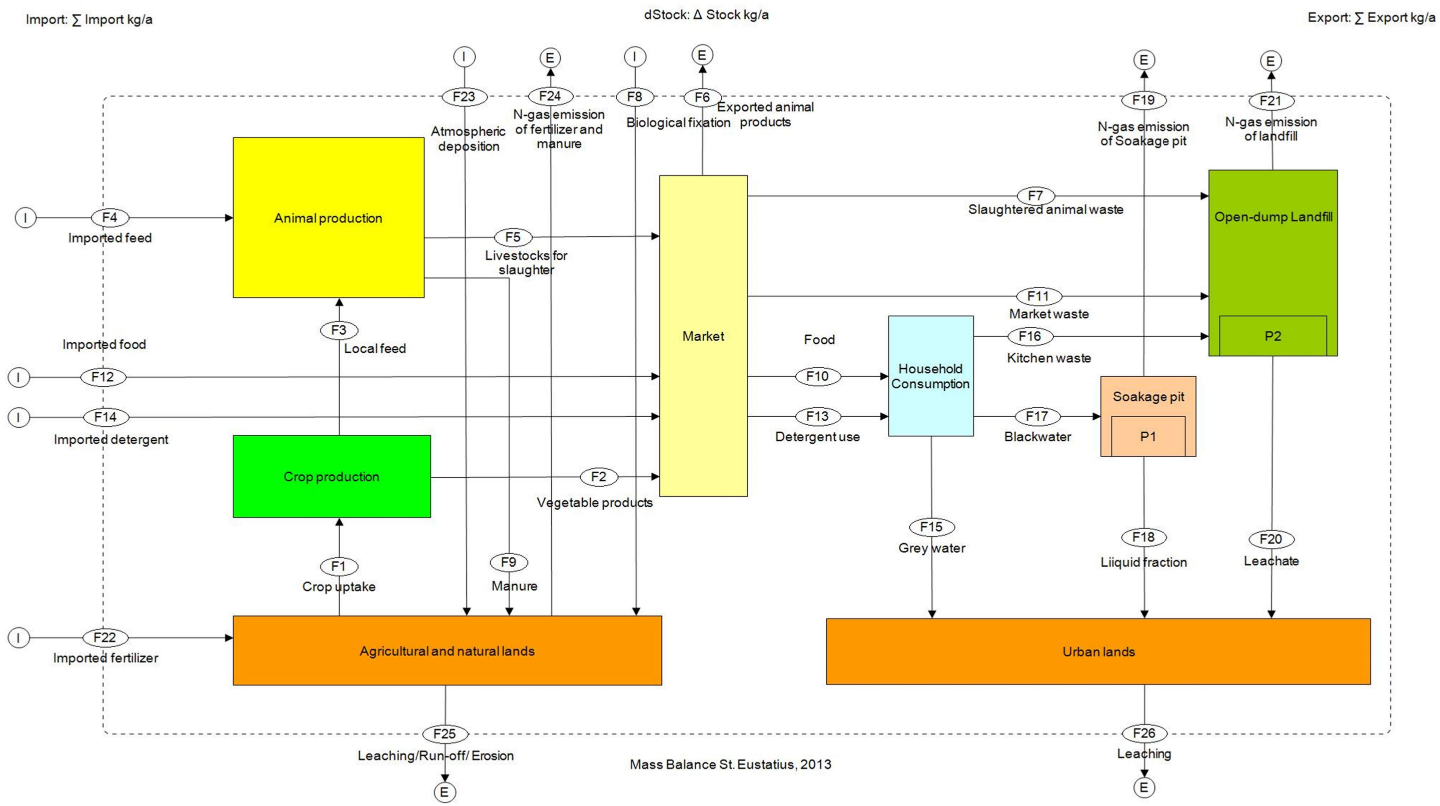

Figure 5.1 Schematic representation of baseline conditions using STAN 2.5; based on Firmansyah et al. (2017)

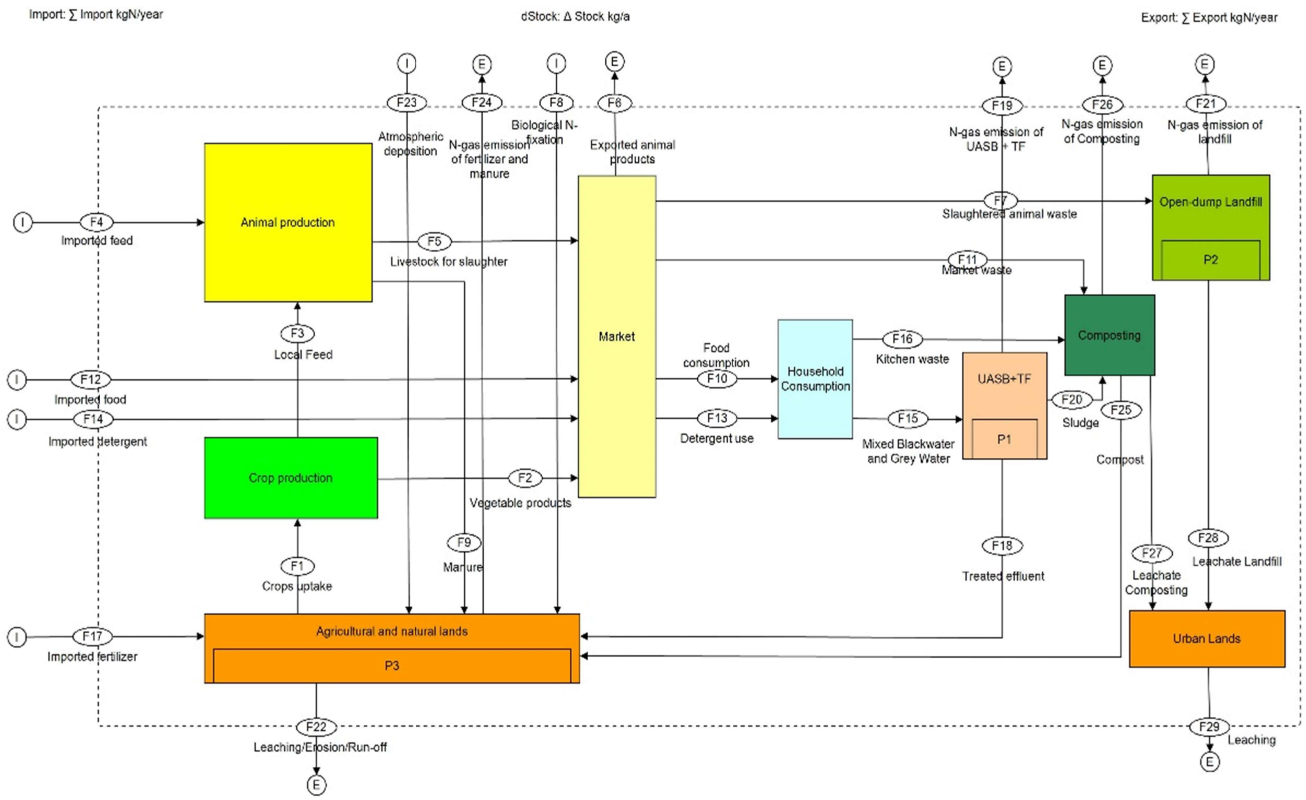

Figure 5.2 Schematic representation of future conditions (new system) using STAN 2.5; adapted from Firmansyah et al. (2017)

5.2.6 Data sources and quantification of systems

5.2.6.1 Household consumption

N and P flows to the household consumption sub-system were calculated based on the total food consumed and the use of detergents by inhabitants on the island. Compared to the baseline (Firmansyah et al., 2017), the P content of detergents was modified from approximately 783 kgP/year in the baseline to phosphate-free detergents in the present study.

5.2.6.2 Sanitation concept (UASB + TF)

The N and P content of treated effluent (F18) was calculated based on removal efficiencies. The P content of the sludge (F20) was calculated based on the difference between P content in input (F15; BW and GW) and output (F18; the treated effluent). N content in the sludge (F20) was calculated based on the difference between N input (F15) and N output (F18 and F19). N emission of UASB and TF (F19) was estimated using the IPCC factor for N2O emission due to nitrification in the TF.

5.2.6.3 Composting

Composting received the sludge (F20), kitchen waste (F16), and market waste (F11) for further treatment to produce compost (F25). The sludge will be dewatered prior to the composting process. The composting of the mixture results in gaseous losses (F26) and leaching (F27). The amount of nutrients in the compost (F25) was calculated based on the difference between input (F20, F11and F16) and output flows (F26 and F27).

5.2.6.4 Open-dump landfill

Within this study, input flow of nutrients to the open-dump consists of slaughtered animal waste (F7). In the baseline situation, kitchen waste (F16) and market waste (F11) were also input to the open-dump landfill but these are directed into composting in the new situation. Output flows include leachate of landfill (F28) and nitrogenous gas emission (F21), and a stock (P2) were included to account for accumulation of N and P in the landfill.

5.2.6.5 Agricultural and natural lands

Many N and P flows are linked to the agricultural and natural lands. Compared to the baseline situation (Firmansyah et al., 2017), two new input flows were added: treated effluent (F18) and compost (F25). Nutrient input by these flows can substitute the input through imported fertilizer (F17). Within this sub-system, it was assumed that P reserves in the soil can vary over time, whereas long-term N stock was assumed to be constant (Sutton, 2013). The absence of N accumulation or depletion in the agricultural and natural land sub-system was based on a steady state approach by assuming no change in soil organic matter content (Van Drecht et al., 2003).

5.2.6.6 Urban lands

This sub-system receives nutrients that leach from the composting site (F27) and open-dump landfill (F28). These flows are then leached outside the urban land sub-system containing N. Since P has low content in leachate (Rajabi and Vafajoo, 2012) and generally N and organic matter are found in composting leachate (Roy et al., 2018), it was assumed that leachate does not contain P. Consequently, most P is contained in the compost in solid form.

5.2.6.7 Animal production

Within this sub-system, N and P flows are explicitly shown in the flows of imported feed (F4), locally produced feed (F3), manure (F9), and livestock for slaughter (F5). According to the mass balance principle, manure (F9) was calculated as the inputs of local and imported feed minus the output of livestock for slaughter. N-gas emission from manure and fertilizer (F24) in this sub-system was calculated based on calculation of the N surplus and estimates reported by Sutton et al. (2013) on the division of N loss over gaseous and leaching losses. Estimations of the nutrient flow of imported feed (F4) and locally produced feed (F3) were based on total nutrient requirements for livestock (Firmansyah et al., 2017).

5.2.6.8 Market

The market sub-system consists of the flows of vegetable products (F2), livestock for slaughter (F5), exported animal products (F6), slaughtered animal waste (F7), imported food (F12), imported detergent (F14), food (F10), detergent use (F13) and market waste from supermarkets and restaurants (F11).

5.2.6.9 Crop production and nutrient uptake

The sub-system of crop production includes arable land (horticulture) for vegetable products for local food and pastures for local animal feed. The food products represent a flow to the market sub-system, while the feed products are flows to the animal production sub-system. The crop production sub-system receives input flows of N and P from crop uptake (F1). Crop uptake (F1) was defined as the total amount of N and P in products that leave the agricultural and natural lands. Crop residues that remain on the field are regarded as an internal flow and are not studied separately. N and P in vegetable products (F2) were estimated based on the nutrient content of the products. For the calculations, an average vegetable crop was described in terms of yield and N and P content based on the crops as described in Firmansyah et al. (2017) (See SM Table S4.2). A mixture of different crops can be grown on the island, depending on the demand for different products. N and P in local animal feed (F3) were estimated from the total nutrient requirement of livestock in St. Eustatius.

When nitrogen (N) is applied to agricultural lands, generally only a fraction is recovered in harvested products. The N use efficiency varies between crops and differs between fertilizer management practices. Average values of recovery efficiency of nitrogen (REN) for harvested vegetables were estimated between 30% for current farming practice and 50% for research conditions (Balasubramanian et al., 2013). Variation in REN occurs between vegetable crops, where for example a shallow rooting lettuce or onion crop has a lower REN compared to deep rooting carrots or cabbages (Thorup-Kristensen, 2006). In the present study, a REN of 40% was used for the calculations, describing good farming practice and being the average of the estimated values for current farming practices and research conditions. The range between 30% and 50% was included as well.

Nitrogen availability from compost is relatively low as the nitrogen is organically bound and slowly releases during organic matter degradation. However, compost also supplies nitrogen beyond the year of application, and in a system with regular annual compost application this availability over multiple years has to be taken into account. For the situation of long-term application of compost, a fertilizer replacement value of 40% was used, consisting of 15% from the current application and cumulative 25% from previous applications (van Dijk et al., 2005). Together with the REN of 40% this gives a recovery of total N in compost of 16%.

Phosphorus availability for crops differs from that of N as P is buffered by soils. P stocks in soil can accumulate or deplete over a long time scale, and only a fraction of the P is directly plant-available. From an agronomic point of view, build-up of a low soil P status can therefore be required for sufficient levels of plant-available P and good crop growth. At (very) high soil-P status, some depletion can be needed to prevent environmental impacts. Accumulation or depletion has an impact on the calculated values for P recovery from fertilizers, but over a long time scale, efficiency of fertilizer P use is generally high and approaches equilibrium (Syers et al., 2008). In the present study, we used 100 percent efficiency in the calculations for P from fertilizers and looked at changes in the P stock in the soil. Potential crop production and required cropping area was calculated for both N and P individually from the available amount of nutrient in treated effluent and compost, nutrient recovery and crop uptake. Subsequently, the lowest crop production was taken, and the impact on flows for the other nutrient were recalculated using the N/P ratio of 6.57 of the average vegetable crops (Firmansyah et al., 2017).

5.2.7 Uncertainty Analysis

The method of Hedbrant and Sörme (2001) was used to analyse the uncertainty of the data of the present study. This method is based on the categorisation of data sources. Each data set was assigned an uncertainty level corresponding to an interval established by an uncertainty factor, corresponding to the representativeness and accuracy of the data source and resulting in an estimated uncertainty range. Since the method of Hedbrant and Sörme (2001) produces asymmetrical intervals as uncertainty, the method of Laner et al. (2015) was applied to modify the asymmetrical intervals into symmetric intervals for use with the STAN software. In this adaptation, the uncertainty factors were converted into coefficients of variation (CV) (Table 5.2). Laner et al. (2015) define the CV as the mean value plus two standard deviations, with a symmetric interval around the mean corresponding to a 95% confidence interval. Detail CV value for each flow can be seen in Table S4.3. The insert value into STAN model were then reconciled to calculate the final value for each flow (Table S4.4).

Table 5.2. Uncertainty level with corresponding uncertainty factors and coefficient Variance (CV) applied for different data sources, adapted from (Firmansyah et al., 2017)

Level	Uncertainty factor	Coefficient Variance (CV)	Information source	Example
1	1.11	±10%	Official national/local statistics, published paper/report related to St. Eustatius or in the region of Caribbean	Food consumption data
2	1.33	±25%	Unpublished reports, published paper/report from global study	Animal production data
3	2	±50%	Experts estimation	Local agricultural production

5.3 Results

5.3.1 Effect on overall balance

Figure 5.3 and Figure 5.4 show the N and P balance on the island after application of the new sanitation concept and use of recovered products in agriculture. Recovered products from domestic waste(water) are available in the form of treated effluent (217628 m^3/year, 11729±10% kgN/year; 1679±18% kgP/year) and compost (4446±64% kgN/year; 724±17% kgP/year). These amounts of nutrients replace imported fertilizer and, considering the nutrient use efficiency of N and P, around 142 ha of land can be used for agricultural production. This area is based on N availability, and the surplus of P gives some accumulation of P in these agricultural lands. It has been calculated that 5403±54% kgN/year and 822±54% kgP/year can be taken up in local food products that are distributed to the market. In total, crops take up 26480±15% kgN/year and 5032±12% kgP/year which used for local animal feed (21077±13% kgN/year; 4210±14% kgP/year) and local food. The additional local production of almost 4000 tons of fresh vegetable products replaces part of the amount of imported food. Nutrients in imported food still contain 14355±27% kgN/year and 1566±36% kgP/year.

In the new system, the total nutrients exported is around 57423±10% kgN/year and 356±20% kgP/year. The exported nutrients are contained in the exported animal products (595±29% kgN/year; 215±28% kgP/year) and the remaining nutrients are lost to the environment. In the agricultural and natural lands, nutrients are lost to the environment by N leaching (31660±19% kgN/year), N-gas emissions (21108±16% kgN/year), and erosion/run-off containing P (141±27% kgP/year). During the composting process, some N is lost through gaseous emissions (2006±25% kgN/year) and some through leaching (1489±25% kgN/year). The practice of open dump landfill still contributes to N gas emission (137±29% kgN/year) and leaching (171±25% kgN/year). Leaching from urban lands comprises the leaching from the open-dump landfill and from composting, together 1660±23% kgN/year.

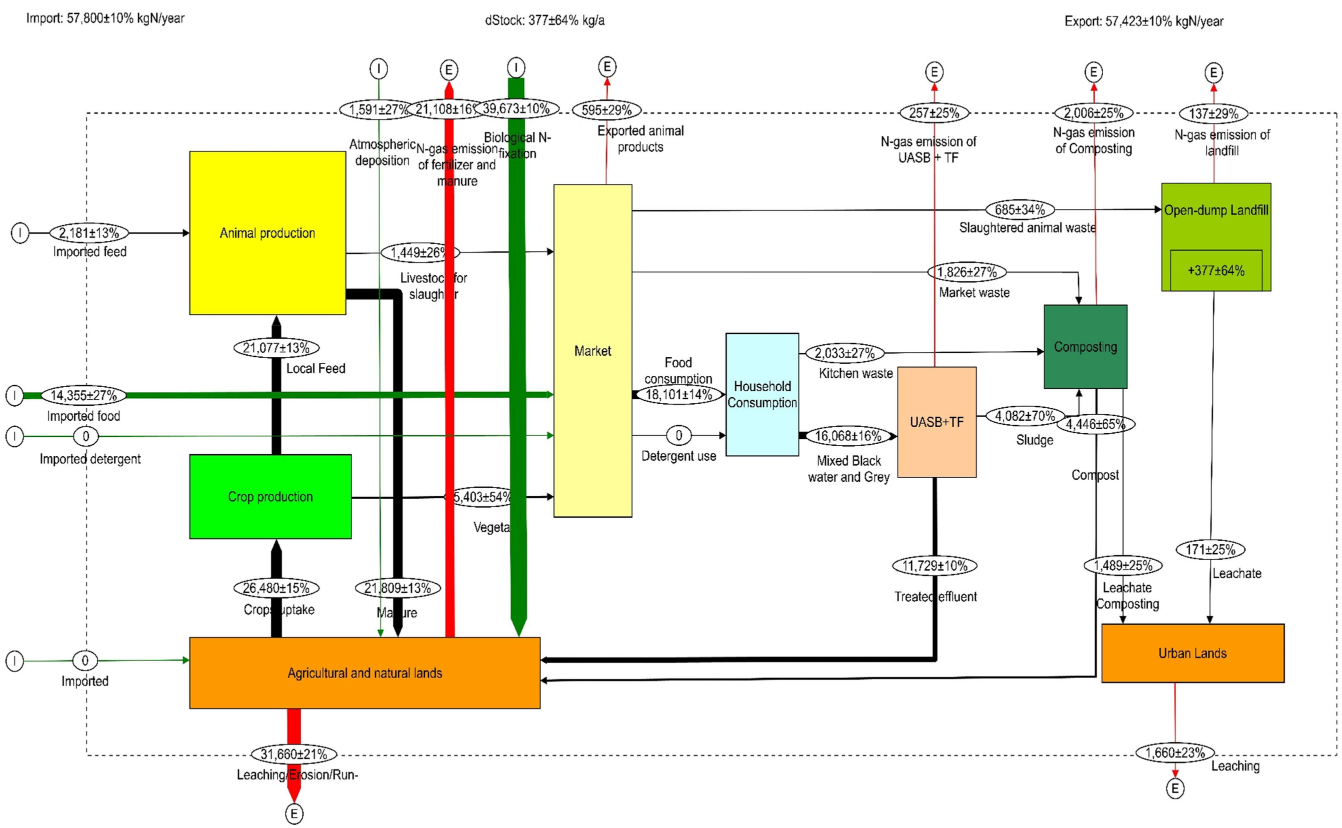

Figure 5.3 Nitrogen balance for the whole island with nutrient recovery from domestic waste and wastewater and reuse in agriculture

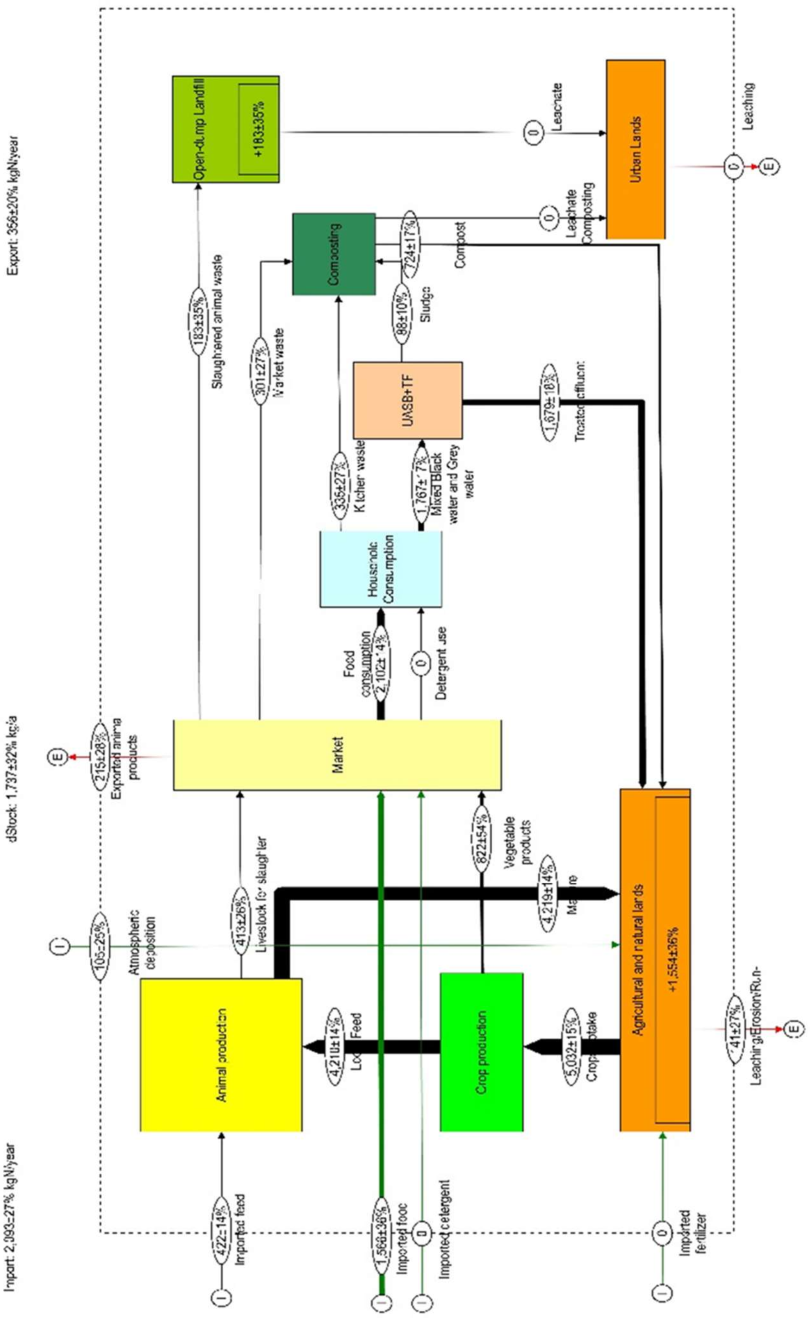

Figure 5.4 Phosphorus balance for the whole island with nutrient recovery from domestic waste and wastewater and reuse in agriculture

5.3.2 Comparison with Baseline conditions

Compared with the baseline conditions (no reuse of nutrients in agricultural lands), the new system added or removed some flows, while changing other nutrient flows (Table 5.3). In the new system, imported fertilizer is fully replaced by nutrients retrieved from domestic waste and wastewater, and there is increased crop production on agricultural land to reuse the recovered nutrients from domestic waste and wastewater. This increases nutrient flows in local food vegetables by a factor 117. The increased local crop production replaces imported plant-based food and reduces the amount of imported nutrients by 27% for N and 34% for P. N-gas emission of fertilizer and manure and leaching from agricultural and natural land has increased by factor 1.2. The BNF flow has changed because of the conversion of lands into arable land, resulting in a decrease of N by 4%. Composting of sludge, kitchen waste and market waste and the treatment of domestic sewage still contribute to nutrient emission and leaching, but in lower amount. In the urban land, leaching has decreased by 89%. The nutrient losses from the open-dump landfill are reduced by 85% for N-gas emission and leaching. In total, the application of the new system will reduce the nutrient losses to the environment by 4 % for N compared to the baseline conditions. P will remain the same as most of it accumulates in the soil.

Table 5.3 Comparison of baseline condition (Firmansyah et al., 2017) and new system with agricultural use of recovered nutrients (this study) for flows that differ between both systems.

Nutrient Flows	**Baseline condition (Firmansyah et al., 2017)**	**New system**	**Relative change**
Total nutrients exported (products + emissions)	59890±9% kgN/year	57423±10% kgN/year	-4%
	356±20% kgP/year	356±20% kgP/year	No change
Total nutrients loss to the environment	59295 kgN/year	56828 kgN/year	-4%
Imported food	19712±13% kgN/year	14355±27% kgN/year	-27%
	2381±27% kgP/year	1566±36% kgP/year	-34%
Agricultural and natural lands			
• Area with food crops	3.6 Ha	142 Ha	+factor 39
• Crop uptake (food+feed)	21123±13% kgN/year	26480±15% kgN/year	+factor 1.25
	4217±14% kgP/year	5032±12% kgP/year	+factor 1.2
○ Local food/vegetable products	46±54% kgN/year	5403±54% kgN/year;	+factor 117
	7±54% kgP/year	822±54% kgP/year	+factor 117
• P accumulation in the agricultural and natural lands	136±115% kgP/year	1554±36% kgP/year	+factor 11
• Biological Nitrogen Fixation	41430±12% kgN/year	39673±10% kgN/year	-4%
• Imported fertilizer	390±50% kgN/year	0	No import
	170±50% kgP/year	0	No import
• Leaching from agricultural and natural lands	26460±19% kgN/year	31660±19% kgN/year	+factor 1.2
• N gas emission from agricultural and natural lands	17637±15% kgN/year	21108±16% kgN/year	+factor 1.2
• P Erosion/run-off	141±27% kgP/year	141±27% kgP/year	No change

Nutrient Flows	Baseline condition (Firmansyah et al., 2017)	New system	Relative change
Waste and wastewater treatment in the urban lands system[1]			
N-gas emissions from wastewater treatment	0	257±25% kgN/year	emission
N-gas emissions from composting	0	2006±25% kgN/year	emission
N gas emission from open-dump landfill	932±29% kgN/year	137±29% kgN/year	-85%
Leaching of urban lands	14266±18% kgN/year	1660±23% kgN/year	-89%
• Leaching from wastewater treatment	13175±19% kgN/year	0	No leachate
• Leaching from composting	0	1489±25% kgN/year	leachate
• Leaching from open-dump landfill	1091±14% kgN/year	171±25% kgN/year	-85%
Accumulation in soakage pit	2893±125% kgN/year	0	No accumulation
	512±102% kgP/year	0	No accumulation
Accumulation in Urban lands	2038±18% kgP/year[2]	0 kgP/year[3]	No accumulation
Accumulation in open-dump landfill	2521±33% kgN/year	377±64% kgN/year	-85%
	819±17% kgP/year	183±17% kgP/year	-78%
Treated effluent and compost to agriculture	0	16175 kgN/year	Reuse in agriculture
	0	2403 kgP/year	Reuse in agriculture

1 Baseline: GW and BW in soakage pit, KW and MW to landfill; New system: GW+BW+KW+MW in UASB+TF and composting.
2 Includes 783 kgP/year from detergents. In new system P-free detergents are used.
3 Accumulation of P in landfill is reported there.

5.5 Discussion

The use of treated domestic wastewater (liquid fertilizer) and compost (solid fertilizer) from KW, market waste and sludge on the tropical island St Eustatius as described in this paper will reduce the import of fertilizer, increase agricultural production and therefore reduce food import. For the increased agricultural production, the area of arable land increases to 170 ha at the cost of pastures and shrubland. Such land transformation may require further socio-economic study, but areas with current thorny woodland have been farmland in the past (de Freitas et al., 2014).

Feed import was not reduced, as we assumed all the recovered nutrients are used in arable land for food production. The number of animals was also not changed in the new system. The arable land likely has to be fenced to protect the crops against free roaming animals, reducing their accessible area by about 8%. We assume no change in consumption of animal products, but possibly the number of animals can be reduced on the island, which can reduce the negative effects on local vegetation (Debrot et al., 2015).

Although the reuse of nutrients from domestic waste and wastewater in agricultural land has the potential to increase agricultural production, the application in practice is challenging. The liquid effluent is not free of pathogens (Yaya-Beas et al., 2016) and can contain micropollutants (Butkovskyi et al., 2015). However, to reduce health risks, different guidelines and regulations are available for agricultural use of different wastewater flows (FAO, 1992, WHO, 2006, Alcalde-Sanz and Gawlik, 2017, Shoushtarian and Negahban-Azar, 2020). These guidelines are based on the pathogen level in the products and include crop characteristics, irrigation method, drinking water source protection, control of the storage and distribution system, irrigation schedule, education and training, and signage.

Generally, secondary and tertiary treatment of wastewater is required to comply with water quality requirements for wastewater reuse in agriculture (Shoushtarian and Negahban-Azar, 2020). From the initial pathogen content of domestic wastewater (Fecal coliform 108 CFU/100 ml) (Metcalf et al., 2003), the application of UASB+TF system as used in our study can remove pathogens up to 4 log removal (Kujawa, 2005, Tawfik et al., 2006). However, a review of (Al-Gheethi et al., 2018) indicated that the concentration of faecal indicators in treated wastewater and biosolids is still high even after treatment. Hence, additional treatments or advance technologies may be needed to ensure the safety of wastewater reuse in agriculture (Jin et al., 2013). This can be the application of disinfection process such as ultraviolet irradiation (Liberti et al., 2003), ozonation, filtration technologies, storage of treated sewage, heat pasteurization, or solar disinfection (Al-Gheethi et al., 2018).

The applications of compost as a product from co-composting process of municipal solid waste (kitchen and market waste) and sludge (dewatered sludge) has been applied in many places and can be a sustainable solution of waste management (Semiyaga et al., 2015, Danso et al., 2017). Co-composting of these waste streams has the advantage that kitchen waste and market waste contain more biodegradable organic matter, and is complementary to the sludge that is rich in nutrients and microbes, which can shorten the composting period (Ma et al., 2016, Zhang et al., 2018). The use of compost is regarded as safe when most of the pathogens have been inactivated during the composting process (Dumontet et al., 1999). In order to inactivate the pathogens, temperature and the length of exposure are the most important factor during the composting process (Wilkinson, 2007). Exposure to of about 55-60°C for at least 3 days during composting is usually sufficient to kill the vast majority of enteric pathogen (Déportes et al., 1995). We expect a safe compost with low amounts of pathogens can be produced from these materials. A proper monitoring of the compost process is however needed.

The use of compost and treated effluent in the present study has a low risk of heavy metals. Although heavy metals are found in BW and GW (Palmquist and Hanæus, 2005, Tervahauta et al., 2014), these flows can be considered safe as the original source of the heavy metals is from human food and there is no input from industrial wastewater and rainwater.

Based on the health and safety guidelines, sub-surface drip irrigation is the recommended method to apply the treated effluent as it limits contact of plants with pathogens. It is an effective and efficient method to spread the liquid-based fertilizer types, though care is needed to prevent clogging of the system (Capra and Scicolone, 2007). The products can be distributed both through surface and sub-surface irrigation method, but the study of (Cirelli et al., 2012) indicated that sub-surface drip irrigation method using treated domestic wastewater has better performance compared to surface drip irrigation method because of a lower risk of pathogens in the crop.

Another challenge in reusing wastewater in agriculture is related to matching supply of water and nutrients with demand for water and nutrients. A certain demand for irrigation water is needed, as application of the effluent for fertilization purposes only will induce nitrate leaching in wet periods. Prolonged periods with a precipitation surplus therefore complicate fertilization with effluent as water is not needed and nutrients are (especially nitrogen as phosphorus also comes available from soil reserves). On the other hand, prolonged dry periods require large amounts of irrigation water, and nutrients may be supplied in quantities above crop demand. For a cropping season, water and nutrient supply only roughly needs to match crop demand as there is some flexibility because of water and nitrogen retention in the soil profile. Better finetuning can be achieved by either adding additional water for irrigation or adding additional fertilizer.

As water application is driving nutrient input in case of use of effluent, and as water input affects potential nitrate leaching, a storage tank or pond system is needed as a buffer to deal with differences in supply and demand. This is valid on the short term of hours and days, as production of treated wastewater does not exactly match the irrigation events. It is also valid on a longer term of days or weeks, as irrigation water demand is determined by the weather conditions, especially rainfall. Wastewater production is relatively stable over time, but irrigation water demand varies. In the context of St. Eustatius, a closed storage tank is preferred to collect treated wastewater and to prevent water losses through evaporation. A minimum storage capacity for two weeks wastewater production is assumed to overcome the variation in rainfall. The assumption of at least two weeks for collecting the effluent for reuse is based on the distribution of rainfall and monthly number of rainy days. For the centralized UASB and TF system and with the volume of treated effluent of 153 l/cap per day, the minimum size of storage capacity is around 8,300 m^3.

Crop production was limited by N availability, and fertilization with the treated effluent and compost caused a surplus of P in agricultural land of 8.2 kg P/ha/year. This will probably be advantageous for crop production in the short term as plant-available P in the soil will increase. However, in the long run, too high P accumulation in the soil can cause P emissions. Options to reduce the P surplus is through a relative increase of the N input to balance input of both N and P with export by crops. This can be achieved by chemical N fertilizer or preferably by the cultivation of leguminous crops in the rotation for biological N fixation. Then, increased crop yield or increased production area is needed.

Currently, the area for crop production on the island has to increase (to 142 ha) if all recovered nutrients in the form of compost and treated effluent are reused in agriculture. The calculations were based on an average crop as derived from Firmansyah et al. (2017), but improved cropping practices with higher yields will require a lower area. One way to achieve this can be through a hydroponics system in which in which the crops are grown on the treated effluent under protected and soil-less environment (Magwaza et al., 2020).

5.6 Conclusions

The applied SFA model can simulate the effects of agricultural reuse of nutrients recovered from domestic wastewater and organic wastes on the overall nutrient balance and environmental impacts at the tropical island St Eustatius. To use all recovered products (treated effluent and compost) for crop production, the area of arable land needs to increase from 3.6 ha to 142 ha at the expense of the area of pasture and shrub land. N leaching at the agricultural land increases, but overall nitrogen losses from the island reduced by 4%. P losses remain constant, but now P is used for food production and some P accumulates in agricultural soil instead of in soakage pits or landfill.

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CHAPTER 6

General Discussion

6.1 Introduction

This thesis addressed several key sanitation planning challenges related to the recovery and reuse of resources from domestic waste(water). The investigation of work of previous scholars in the introduction chapter showed the lack of an approach and tool to identify the most appropriate technology and its most suitable scale in a given local context. Moreover, future uncertainty has not been properly accounted for in the planning of sanitation systems. The combination of selecting appropriate technology and accounting for uncertainty is expected to improve local resources management, reduce risks, provide robust and flexible strategies, and support decision making in urban-agricultural planning. Therefore, the aim of this thesis was to develop a planning approach to support recovery and reuse of nutrients, to couple sanitation-agricultural systems, while considering different future development scenarios. The four sub-objectives were:

1. To develop a framework that facilitates a structured analysis of the link between sanitation and agricultural systems with regards to nutrient supply and demand;
2. To identify strategies for implementation of sanitation concepts in urban areas to recover nutrients from domestic waste(water) and reuse in agriculture;
3. To assess the effect of different future development scenarios on the performance and selection of sanitation concepts;
4. To assess the impact of agricultural reuse of nutrients for optimising nutrients recovery from domestic waste(water).

The four research chapters of this thesis addressed each of these sub-objectives individually or combined a maximum of two elements. However, as described in **Chapter 1**, an appropriate planning approach should comprise and address all four objectives together. It is the aim of this chapter to describe how the four research objectives, and therefore also the four different methods and approaches developed, can be combined into a sequential planning approach.

6.2 The main components of the new planning approach

The developed planning approach comprises 4 elements: (1) assessment of the current nutrient balance, (2) selection of sanitation concepts based on different sustainability indicators, (3) testing the robustness of the selected technologies under future scenarios, and (4) assessment of the nutrient balance after application of selected sanitation concept (Figure 6.1).

6.2.1 Assessment of the current nutrient balance

Chapter 2 provides an analysis of the nutrient flows on the island using a Substance Flow Analysis (SFA) approach. Different systems like agricultural and natural lands, urban lands, crop production, animal production, market, household consumption, soakage pit, and open-dump landfill were distinguished. This provided insights in how the different systems on the island function with regards to the flows of N and P. Since data collection was challenging on the island, this research also considered the uncertainty of the data and provided a methodology to solve a limited data situation of a studied area.

6.2.2 Selection of sanitation concepts based on different sustainability indicators

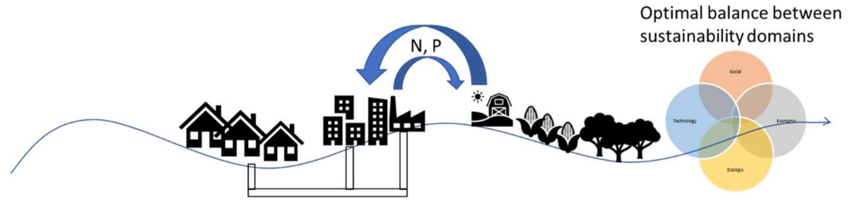
Chapter 3 shows possible technological systems/concepts which were elaborated to assess its performance across different sustainability indicators under four domains of indicators: environmental, technological, social-cultural, and economic. Three decentralized source separation and two centralized concepts were compared across 13 sustainability indicators, showing that the centralised, island scale, UASB+TF treating BW and GW had the best performance.

6.2.3 Selection of sanitation concepts across different future scenarios

Chapter 4 provides a methodological approach that considers the uncertainty of future development which influences the selection and performance of sanitation concepts. Four explorative scenarios were developed to distinguish different future uncertainty through trend analysis. Under these different circumstances, the centralised, island scale, UASB+TF treating BW and GW showed again the best performance.

6.2.4 Assessment of nutrient balance due to the application of the selected sanitation concept

Chapter 5 shows that the centralized, island scale, UASB+TF treating BW and GW was selected to assess the effect on nutrient flows on the island with a focus on the reuse aspects of recovered products in agriculture. This analysis showed that agricultural reuse of recovered products increased local food production, replaced all fertilizer import and part of the food import, and reduced nitrogen losses to the environment.



Planning challenges	Understanding N and P flows under limited data availability	Selecting sanitation technological concepts for resource recovery	Trends and future uncertainty	Effect of N and P reuse in agriculture for closing the nutrient cycles
Planning approach	Substance Flow analysis (SFA)	Concept selection	External scenarios; Multi Criteria Decision Making (MCDM)	Substance Flow analysis (SFA)
Chapter	Chapter 2	Chapter 3	Chapter 4	Chapter 5

Figure 6.1 Elements of the developed planning approach in this thesis

6.3 The new planning approach

This thesis provides a stepwise approach that helps urban planners and policy makers in decision making of sanitation concepts for implementation. The approach takes the following steps (Figure 6.2).

In the first step, an understanding of the mass flows of target elements (e.g. N and P) or goods (food and feed) should be developed. This will aid the assessment of recovery potentials and focus areas in the economy. It is further essential to map the current relationship between sanitation and agriculture and to use this as a starting point to understand how the agricultural system should co-evolve with the sanitation system or vice versa. While this is a rather complex activity for individual sanitation experts or decision makers, increasingly there are national and regional MFAs and SFAs that have been carried out to assess for example energy and nutrient flows (Voskamp et al., 2015, Papangelou et al., 2020, Papangelou and Mathijs, 2021).

In the second step, technological choices must be made in the context of sustainability. With the increasing technological options for sanitation and resource recovery, well founded choices must be made on which sanitation options to select. These choices need to be integrated with the four sustainability domains and generally the optimization should aim for minimal environmental impact and maximal economic and social utility. At the same time, the aim is to recover as many resources as possible to progress towards a circular economy. This ambition leads however directly to the third step in the overall planning framework.

In the third step, the impact of uncertainties on the system must be tested. This will deliver insights for decision makers on which future trends and situations they need to consider, what the consequences are for the technological choices and how they can respond. Specifically, it will allow them to test choices they made in step two for their robustness against future developments. Should this step reveal major shortcomings of selected technologies in terms of their sustainability, it is recommended to revisit step 2, exploring alternative technological options. A challenge of this step is that the creation of scenarios is novel in the context of sanitation planning. However, it is not new to urban planning in general. It is therefore advisable that instead of creating new scenarios, sanitation experts seek the interaction and collaboration with other planners to align scenarios and impact multiple actors.

In the fourth step, combining mass flows and recovery potentials is required. By bringing together insights from previous steps it is possible to estimate the changes required in the agricultural system as a function of the recovery potential. In part, these changes are a simple reflection of changes in mass flows to different crops or parts of network of flows. However, it can be possible that in other agricultural systems these changes are more of qualitative nature, through the replacement of primary inputs to agriculture (e.g., synthetic fertilizers) with different recovered products with the application of different sanitation technologies (Egle et al., 2015, Mehta et al., 2015). Some would argue that this is for actual real-world planning maybe quite a heavy task, but a counter arguments could be that the transition to circular economy happens slowly and that bilateral agreements between sanitation and agriculture emerge (Wielemaker, 2019). New actors on the recovery and reuse process may emerge with various products that can be reused in agriculture.

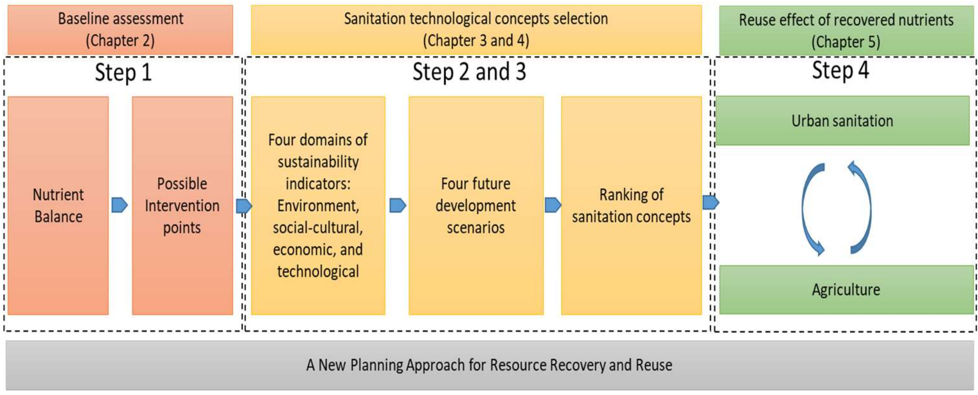


Figure 6.2. Framework of the new planning approach

6.4 Reflection on the application of the new planning approach in St. Eustatius

The application of the planning approach/framework in the context of St. Eustatius was complex and faced some challenges. To start with, data and information on nutrient flows, stocks, and export and import were limited or often not clear to understand. However, this thesis also shows the possibilities to conduct the SFA studies under limited data availability using the methodology developed by Hedbrant and Sorme (2001) and Laner et al. (2014). The methodology dealing with the uncertainty of data has also been applied in other nutrient flow studies (Antikainen et al., 2005, Cooper and Carliell-Marquet, 2013, Laner et al., 2015).

The results showed that produced domestic waste and wastewater on the island are not properly managed. The applied sanitation technologies (soakage pits) and the open dump-landfill result in nutrient emissions and other environmental problems (Firmansyah et al., 2017). Moreover, agricultural production on the island also can be further developed. At present, only < 1% of the food consumed is produced on the island. The crop production is not only limited, but also relies on the use of imported fertilizer. This calls for a better application of technologies that can recover nutrients from domestic waste and wastewater for reuse in agriculture. We argued that the selection of the technologies should consider four domains of sustainability indicators: environmental, economic, social-cultural, and technology, as well as different future scenarios. This is meant to have a trade-off and proper selection of the technologies that can perform under different future conditions. However, the technologies should also consider the full train of technologies from collection, transport, treatment and reuse. The assessment based on 13 different sustainability indicators and four developed future scenarios showed best performance with a centralised, island scale, UASB +TF treating blackwater and greywater and the application of composting for organic domestic waste and sludge. With this technological concept, nutrients are recovered in the form of treated effluent and compost. Proper agricultural use of these products can reduce overall nutrient losses, increase agricultural production, and reduce the amount of imported fertilizer and food.

The developed approach took the nutrients N and P as an example of resources that can be recovered from domestic waste and wastewater and reused in agriculture. The assessment based on these nutrients implicitly includes the recycling of organic matter and other nutrients as these are present in the recovered products. A separate study on those substance will add details to a better planning of sanitation and agricultural systems.

6.5 Contribution of the new planning approach

This thesis contributes to the development of sanitation planning considering nutrient recovery from domestic waste and wastewater and reuse in agriculture. St. Eustatius was selected as the case study as it provides a clear delineated area to assess the link between sanitation and agriculture focusing on nutrients (N and P) recovery and reuse. The conditions in St. Eustatius might be similar to other small islands that would like to develop a circular metabolism. This is because the islands are prone to natural and environmental disasters, and remoteness (Briguglio, 1995, Adrianto and Matsuda, 2004, Dropsy et al., 2020). However, the developed approach can also be applied to other regions to select sanitation concepts that can be coupled with agricultural systems.

The developed approach is intended to provide quantification methods that combine quantitative and qualitative assessment of sustainability indicators across four domains of indicators. Transdisciplinarity is included in the approach, combining different fields of expertise, viz. sanitation (environmental technology), agriculture, and land use planning as well as involvement of local and regional stakeholders of St. Eustatius.

The approach provided in this study is generic and potentially applicable in different contexts under different considerations. The steps in the approach can be followed by decision-makers and urban planners to design sustainable sanitation concepts considering different sustainability indicators and future development trends. The quantification methods applied in the study can be generalized and applied in other contexts. The methodologies for selection of the technologies and sustainability indicators can be applied in other tropical regions, and the methodologies for scenario development and Multi Criteria Decision Making (MCDM) can be adopted in non-tropical regions.

When decision-makers and urban planners use the stepwise process and a set of defined indicators, their choices will become more explicit, transparent and future-proof. Thereby, the approach will contribute to better decision making, lasting implementation, and eventually to the achievement of the SDGs (Haag et al., 2019). Not only can the recovery and reuse of resources from domestic waste and wastewater contribute to the achievement of SDG 6 (clean water and sanitation), but also other SDGs such as SDG 12 (sustainable consumption and production) and can help improve food security (SDG 2, zero hunger) (Andersson et al., 2016). The results of the approach for resource recovery and reuse can also attribute to the development of liveable cities of tomorrow, achieving SDG 11 (sustainable cities and communities), SDG 1 (no poverty) and SDG 6 (decent work and economic growth) (Andersson et al., 2016).

6.6 Future Research Agenda

This thesis focused primarily on the development of a planning approach for resource recovery and reuse considering the baseline and future development of a studied area. The approach enables the selection of the best performing sanitation concept across selected sustainability indicators. However, future research is still needed to improve the approach to support resource recovery and reuse and enable decision making on the application of the technologies.

6.6.1 Sanitation and agricultural systems

The pre-selection of sanitation concepts for comparison should be executed carefully considering local conditions and supported through a literature review of possible technologies and concepts (Spuhler et al., 2020). The selection of the five sanitation concepts incorporated in this study (Chapter 3) was done based on the possibility to use recovered fertilizer products in a continuous crop agricultural system as prevailing under tropical conditions. Under non-tropical conditions, where fertilizers cannot be applied in winter, the sanitation concepts to be considered will become more complex because less bulky fertilizer products are needed to limit (winter) storage volumes. Moreover, technologies selected in this study are regarded as primary and secondary treatments. Although pathogens are reduced in the different concepts, disinfection of the recovered products for reuse in agriculture may be necessary depending on the method of application and crop selection (Shoushtarian and Negahban-Azar, 2020). A risk assessment is needed for the use of recovered products from different application of sanitation technologies.

In **Chapter 5**, only two products are evaluated for reuse in agriculture, viz. compost (solid product) and treated effluent (liquid product), based on the selected sanitation concept in Chapter 4. When treated effluent and compost are both effectively used in agriculture, this gives a high degree of circularity as nutrient losses in the treatment system are limited and the two output streams, liquid effluent and sludge are both used in agriculture. Only during composting, almost 20% of the nitrogen is lost. Fertilization in agricultural goes together with nutrient losses, especially of N, as not all applied N is absorbed by crops. Increasing the agricultural area will therefore increase nutrient losses from agriculture. In our system of St. Eustatius, these increased agricultural losses were lower than the reductions due to implementation of proper sanitation, leading to an overall reduction of N losses of 4%.

In the current exploration, the average N and P demand of the seven vegetable crops currently grown on the island (baseline situation) was used as crop production data. Hence, a more detailed study on the nutrient demand of the crops is required to identify the supply potential from domestic wastewater. This is meant to match the demand and supply of the nutrients. Variation in these data is possible as different tillage systems might be applied, other crops may be grown and crops differ in nutrient use efficiency and production level (nutrient offtake). Root crops, for example, generally have higher yields and a higher nutrient use efficiency than vegetable crops. Cultivation of more root crops therefore results in a lower demand for arable land (ha) than with the current average vegetable crop. Similarly, the food system is likely to have to increase in efficiency also with regards to fodder crops and animal feed production. In the context of the role of farm animals in circular food systems, Van Zanten et al (2019) suggested that, amongst others, the prevention of N and P leakage as well as the recycling of human excreta are vital. In addition to other crops, other cultivation methods and fertilizer strategies can also affect crop yield and nutrient losses. Despite these possible variations, the currently used average crop data give a good indication in the assessment of opportunities for matching supply and demand.

6.6.2 Sustainability indicators

This thesis aimed to include quantitative and qualitative indicators in the assessment of the performance of sanitation concepts. However, for the qualitative indicators representing technological and social-cultural indicators, the assessment is only based on interviews and discussion with sanitation experts experienced in the application of the studied concepts. There is a need to include local people to provide their views on the application of the resource recovery concepts; this needs a methodology to explain the sanitation concepts to laymen. Chapter 4 includes the perspectives of local and regional stakeholders on the possibilities and implications of future development for St. Eustatius, derived from interviews and discussion on the application of resource recovery concepts and reuse possibilities in agriculture on the island. According to the interviewees, a circular economy for the island and other neighboring islands is of great importance. For future research more local stakeholders could be involved, improving the institutional and social expertise about a given context. Likewise, other studies showed that local stakeholder knowledge supports the application of resource recovery and reuse (van Vliet et al., 2011, Poortvliet et al., 2018), so stakeholders should be involved to provide wider and better views for sanitation planning, which may affect the selection of technologies.

6.6.3 Scenario development

The new approach relies on the application of external scenarios to portray future development. However, additional techniques can be applied to explore development trends, such as weak signals or wild cards (Dammers et al., 2014, Takala and Heino, 2017). These techniques can capture unforeseen or disruptive events, such as the global pandemic of Covid-19, which are typically outside the scope of external scenarios. Furthermore, in the current approach we used the simple multi-criteria technique of Weighted Sum Model. Future research can explore other multi-criteria techniques, such as Analytic Hierarchy Process (AHP) (Bao et al., 2016), or Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Wolman et al., 2018). Future research may also address the relative complexity and required resources of the approach, and possibilities to communicate it in a simpler way to stakeholders, in order to make it more suitable for participatory planning processes.

6.6 Conclusion

This thesis aimed to develop a planning approach to support recovery and reuse of nutrients and couple the sanitation and agricultural systems, while accounting for different future development scenarios. The approach starts with a baseline assessment by applying the SFA approach for the assessment of coupled agricultural and urban systems (sanitation) under limited data availability. Through the SFA, sources of nutrient losses and stocks that are potentially available for agricultural production are identified. The second steps involves the selection of a sanitation concept for application, based on four domains of sustainability indicators, viz. environmental, technological, social-cultural, and economic indicators. A pre-selection of sanitation concepts is required, based on a review of scientific literature and studying local conditions. The selection process involves iterations of drafting, redrafting and discussing flow diagrams of sanitation concepts, including collection, transport, treatment and reuse. This thesis shows a need to analyse development trends influencing the performance and selection of sanitation concepts. The trends are long term and not under the control of the local decision makers that can be used to build external scenarios. This thesis also developed an MCDM model to assess and rank the sanitation concepts for selection under different future scenarios. This included quantification of the performance of sanitation concepts for each sustainability indicator, and normalisation of the indicator values to allow for mutual comparison. Moreover, this thesis assesses the effect of recovered nutrients from the best performing sanitation concept for reuse in agriculture. The combination of the research chapters in this thesis leads to the determination of the potential mitigation option for nutrient loss and emissions on an island scale, this being the necessary first step towards a circular nutrient system. This will contribute to the achievement of several SDGs, especially SDG 6 related to clean water and sanitation.

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Supplementary Material

S1. Supplementary Material Chapter 2

Table S1.1 List of quantification methods per flow and the assumptions

Flow	Description	Quantification method	Assumptions[1] and references
F1	Crop uptake	F1=F2+F3	Calculated from the mass balance of "Crop production" sub-system
F2	Vegetable products	Crop production (kg/year)* N,P contents	Crop production (Hazel, 2014); N and P content per kg of tomatoes (1.5 gN/kg, 0.22 gP/kg), cucumber (1 gN/kg, 0.15 gP/kg), lettuce (2 gN/kg, 0.23 gP/kg), water melon (1 gN/kg, 0.09 gP/kg), spinach (4.2 gN/kg, 0.46 gP/kg), pineapple (0.7 gN/kg, 0.09 gP/kg), pumpkins (1.8 gN/kg, 0.44 gP/kg) (Souchi, 2001)
F3 F4	Feed	Total feed: (Live animals * Nutrient (N,P) requirement per animal (kg/year)*correction factor)+ (Live animals for slaughter*Live weight (kg per head)*N,P contents per kg animals weight)	Number of livestock (Debrot et al., 2015); Nutrient (N,P) requirement per animal for maintenance of beef cattle (67.5 gN/day, 13 gP/day) (NRC, 2000), goat (5.3 gN/day, 1 gP/day) (NRC, 2007), and sheep (6.4 gN/day, 1.3 gP/day) (NRC, 2007); correction factor of beef cattle (0.6), goats (1), and sheep (0.8) (FAO, 2015); Live animals for slaughter

		Imported feed (F4): Fenced animals * Ratio of imported feed consumed by fenced animals Local feed (F3): Total feed – F4	(LVV, 2014); Live weight based on Tropical Livestock Unit (TLU) of beef cattle (250 kg), goats (30 kg), and sheep (30 kg) (FAO, 2015); N and P content per kg animal live weight of beef cattle (27 gN/kg, 7.4 gP/kg), goat (24 gN/kg,7.9 gP/kg), and sheep (25g N/kg,7.8 gP/kg) (Bruggen, 2007); Number of fenced animals (20% of live animals); Ratio of imported feed consumed by fenced animals (50%)
F5	Livestock for slaughter	Livestock for slaughter* Live weight (kg per head)*N,P contents per kg animal live weight	Number of livestock for slaughter (LVV, 2014); Live weight based on Tropical Livestock Unit (TLU) of beef cattle (250 kg), goats (30 kg), and sheep (30 kg) (FAO, 2015); N and P content per kg livestock weight of beef cattle (27gN/kg, 7.4gP/kg), goat (24gN/kg,7.9 gP/kg), and sheep (25 gN/kg,7.8 gP/kg) (Bruggen, 2007)
F6	Exported animal product	Livestock for slaughter (export only)* Live weight (kg per head)*N,P contents per kg animal live weight - Slaughter waste of	Number of livestock for slaughter (export)= exported animal products (carcasses)/fraction animal to carcass (LVV, 2014); fraction animal to carcass of beef cattle (0.635), goats and sheep (0.5) (Smit, 2014); N

		exported products (kg)* N,P contents	and P content per kg livestock weight of beef cattle (27 gN/kg, 7.4 gP/kg), goat (24 gN/kg,7.9 gP/kg), and sheep (25 gN/kg,7.8 gP/kg) (Bruggen, 2007); Slaughter waste of exported products=total live weight-carcass weight; N and P content per kg slaughter waste is assumed equal to the meat of beef cattle (22.2 gN/kg, 2 gP/kg), goats and sheep (20.6 gN/kg, 1.8 gP/kg) (Foodsel, 2008)
F7	Slaughtered animal waste	Slaughter waste from exported products (kg)* N,P contents + Live animals for slaughter (local only)* Live weight (kg per head)*N,P contents - Meat products (kg)*N,P contents	Slaughter waste of exported products=total live weight-carcass weight; N and P content per kg slaughter waste is assumed equal to the meat of beef cattle (22.2 gN/kg, 2 gP/kg), goats and sheep (20.6 gN/kg, 1.8 gP/kg) (Foodsel, 2008); Number of live animals for slaughter (monthly local consumption: beef cattle (4), goats (20), sheep (10) (LVV, 2014); Live weight based on Tropical Livestock Unit (TLU) of beef cattle (250 kg), goats (30 kg), and sheep (30 kg) (FAO, 2015); Meat products=Total live weight*Fraction meat from total weight of beef cattle

			(0.381), goats and sheep (0.3) (Smit, 2014); N and P content per kg meat of beef cattle (22.2 gN/kg, 2 gP/kg), goats and sheep (20.6 gN/kg, 1.8 gP/kg) (Foodsel, 2008)
F8	Biological nitrogen fixation	Type of land (ha)*N fixation factor (kg/ha)	Total pastures (140.1 ha), shrub and bush rangeland (768 ha), forest (866 ha) (Smith et al., 2013); N fixation factor for grassland (2.7 kgN/ha), forest and shrubland (23 kgN/ha) (Cleveland et al., 1999)
F9	Manure	F9=F3+F4-F5	Calculated from the mass balance of "Animal production" sub-system
F10	Food	Total food protein supply (g/cap per day)*N,P contents	N=0.13*Total food protein (gN/cap per day); P =0.011* (Total food protein+plant food protein) (gP/cap per day) (Vinnerås and Jönsson, 2002); Total food protein supply for Netherland Antilles is 93.2 g/cap per day (FAOSTAT, 2014);
F11	Market waste	Market waste production*Dry matter content*N,P content	Market waste 35.4 kg/cap per year (DEI, 2014); Dry matter content (40%) (Eggleston et al., 2006), N content 3.16%, and P content (0.52%) (Zhang et al., 2007)

F12	Imported food	F12=F2+F5+F14-F7-F10-F11-F13	Calculated from the mass balance of "Market" sub-system
F13	Detergent use	Detergent use/cap per day*number of population	Detergent use in St. Eustatius is 0.62 kgP/cap per year as a result of equation (1) (Van Drecht et al., 2009)[2]; number of population and tourist is 4093 (CBS, 2014)
F14	Imported detergent	F14=F13	It is assumed that the total detergent used is imported
F15	Greywater	F15=F13	It is assumed that the total detergent is discharged as greywater
F16	Kitchen waste	Kitchen waste production*Dry matter content*N,P content	Kitchen waste is 39.3 kg/cap per year (DEI, 2014); Dry matter content (40%) (Eggleston et al., 2006), N content (3.16%), and P content (0.52%) (Zhang et al., 2007)
F17	Blackwater	F17=F10+F13-F15-F16	Calculated from the mass balance of "Household Consumption" sub-system
F18	Liquid fraction of soakage pit	F17* Transfer coefficient of N,P in liquid fraction of soakage pit	Transfer coefficient in liquid fraction of soakage pit for N (73-91%), and for P (60-82%) (Montangero and Belevi, 2007).

F19	N-gas emission of soakage pit	assumed to be "0"	
F20	Leachate	Total N input to landfill*Transfer coefficient of N in leachate	Transfer coefficient of N in leachate (21-27%) (Wang et al., 2014), No P leaching is assumed
F21	N-gas emission of landfill	Total N input to landfill*Transfer coefficient of N-gas emission of landfill	Transfer coefficient of N-gas emission (16–25%) (Onay and Pohland, 1998)
F22	Imported fertilizer	Fertilizer rate (kg/ha)*total arable land (ha)*N,P contents	1000 kg fertilizer (NPK 13:13:13) was imported to fertilize 1.2 ha (Hazel, 2014). The same fertilizer application rate for total arable land is assumed (833 kg/ha)
F23	Atmospheric deposition	Total land area (ha)*Atmospheric deposition factor (kg/ha)	Total land area: 2109 ha (Smith et al., 2013); N deposition (0.5 – 1 kgN/ha per year)(Galloway et al., 2004); P deposition (0.05 kgP/ha per year) (Tipping et al., 2014)
F24	N-gas emission of fertilizer and manure	F24=(F8+F9+F22+F23-F1)*40% (Sutton, 2013)	Of the surplus, N is lost through ammonia emission (24%), soil denitrification (16%), and N leaching and runoff (60%) (Sutton, 2013)

F25	Leaching/Run-off of N	F24=(F8+F9+F22+F23-F1)*60% (Sutton, 2013)	Of the surplus, N is lost through ammonia emission (24%), soil denitrification (16%), and N leaching and runoff (60%) (Sutton, 2013)
	Erosion/run-off of P	Total land (ha)*average rate of P erosion in three Caribbean islands (kgP/ha per year)*ratio rainfall at St. Eustatius with the islands	Total land (2109 ha) (Smith et al., 2013); average rate of P erosion in Dominica, St Lucia, and St. Vincent (0.134 kgP/ha per year), ratio rainfall is half of the islands.
F26	Leaching	F26=F15+F18+F20	Calculated from the mass balance of "urban lands" sub-system

[1] Where a range is given, the average value is used in the calculations
[2] Estimation of the amount of detergent use and its P content for laundry and dishwashing (F14) follow the equation of (Van Drecht et al., 2009).

$$F14 = \left\{\left(10 - 10[\frac{GDP_{mer}}{20000} - 1]^2\right) * f_{Ldet}^{P} * f_{Ldet}^{Pfree}\right\} + \left\{\left(0.365 * f_{use} * \frac{dose}{pphh} * COV_{DW}\right) * f_{Ddet}^{P} * \left(1 - f_{Ddet}^{Pfree}\right)\right\} \quad (1)$$

Where GDP_{mer} is the national per capita gross domestic product (market exchange rate based GDP expressed in U.S. dollar/cap per year) (29898 US Dollar/cap per year) (WorldBank, 2014), f_{Ldet}^{P} is the P content of laundry detergents (kg/kg) (0.25), f_{Ldet}^{Pfree} is the fraction of P-free laundry detergents (0.72), f_{use} is the frequency of the use of automatic dishwashers (0.64 per day), dose is the weight of the tablets used in automatic dishwashers (30 g), pphh is the average number of persons per household (2.92), COV_{DW} is the fraction of a population with access to an automatic dishwasher (0.42), f_{Ddet}^{P} is the P content of dishwasher detergents (kg/kg) (0.117), and f_{Ddet}^{Pfree} is the fraction of P-free dishwasher detergents used (0.72).

Table S1.2 N and P flows in St. Eustatius with coefficient variance (CV) that is used in STAN 2.5 for data uncertainty, reconciliation and visualisation

Flow	Description	Mass flow & N and P content			
		Mass flow	**CV mass flow**	**N and P content**	**CV N and P content**
F1	Crop uptake	-	-	-	-
F2	Vegetable products	Tomatoes (7650 kg/year), Cucumber (8765 kg/year), Lettuce (3265 kg/year), Water melon (3360 kg/year), Spinach (406 kg/year), Pineapple (1600 kg/year), Pumpkin (4425 kg/year) (Hazel, 2014	50%	Tomatoes (1.5 gN/kg, 0.22 gP/kg), cucumber (1 gN/kg, 0.15 gP/kg), lettuce (2 gN/kg, 0.23 gP/kg), water melon (1 gN/kg, 0.09 gP/kg), spinach (4.2 gN/kg, 0.46 gP/kg), pineapple (0.7 gN/kg, 0.09 gP/kg), pumpkins (1.8 gN/kg, 0.44 gP/kg) (Souchi, 2001)	25 %
F3	Local feed	Cows (1012), goats (2470), sheep (1300) (Debrot et al., 2015)	10%	Nutrient (N,P) requirement per animal for maintenance of beef cattle (67.5 gN/day, 13 gP/day) (NRC, 2000), goat (5.3 gN/day, 1 gP/day) (NRC, 2007), and sheep (6.4 gN/day, 1.3 gP/day) (NRC, 2007)	10%

Flow	Description	Mass flow & N and P content			
		Mass flow	**CV mass flow**	**N and P content**	**CV N and P content**
F4	Imported feed	Cows (1012), goats (2470), sheep (1300) (Debrot et al., 2015)	10%	Nutrient (N,P) requirement per animal for maintenance of beef cattle (67.5 gN/day, 13 gP/day) (NRC, 2000), goat (5.3 gN/day, 1 gP/day) (NRC, 2007), and sheep (6.4 gN/day, 1.3 gP/day) (NRC, 2007)	10%
F5	Livestock for slaughter	Beef cattle (4 per month), goats (20 per month) and sheep (10 per month) (LVV, 2014) Live weight based on Tropical Livestock Unit (TLU) of beef cattle (250 kg), goats (30 kg), and sheep (30 kg) (FAO, 2015)	25%	Beef cattle (27gN/kg, 7.4gP/kg), goat (24gN/kg,7.9 gP/kg), and sheep (25 gN/kg,7.8 gP/kg) (Bruggen, 2007),	10%
F6	Exported animal product	Carcass meat of beef cattle (18583 kg/year), Goat (328 kg/year), Sheep (1126 kg/year) (LVV, 2014)	25%	Beef cattle (27 gN/kg, 7.4 gP/kg), goat (24 gN/kg,7.9 gP/kg), and sheep (25 gN/kg,7.8 gP/kg) (Bruggen, 2007)	10%

Flow	Description	Mass flow & N and P content			
		Mass flow	**CV mass flow**	**N and P content**	**CV N and P content**
F7	Slaughtered animal waste	Beef cattle (4 per month), goats (20 per month) and sheep (10 per month) (LVV, 2014), Live weight based on Tropical Livestock Unit (TLU) of beef cattle (250 kg), goats (30 kg), and sheep (30 kg) (FAO, 2015)	25%	beef cattle (22.2 gN/kg, 2 gP/kg), goats and sheep (20.6 gN/kg, 1.8 gP/kg) (Foodsel, 2008)	25%
F8	Biological nitrogen fixation	Pastures (140.1 ha), Rangeland (768 ha), Forest (866 ha), Bare/sparsely vegetated (151 ha) (Smith et al., 2013)	10%	N fixation factor for grassland (2.7 kgN/ha), forest and shrubland (23 kgN/ha) (Cleveland et al., 1999)	10%
F9	Manure	-	-	-	-
F10	Food	Total food protein supply for Netherland Antilles is 93.2 g/cap per day, otal vegetable/plant protein 34.7 g/cap per day (FAOSTAT, 2014)	10%	N=0.13*Total food protein (gN/cap per day); (Vinnerås and Jönsson, 2002)	10%
F11	Market waste	Market waste (35.4 kg/cap per year) (DEI, 2014)	10%	Dry matter content (40%) (Eggleston et al., 2006), N (3.16%), and P (0.52%) (Zhang et al., 2007)	25%

Flow	Description	Mass flow & N and P content			
		Mass flow	CV mass flow	N and P content	CV N and P content
F12	Imported food	-	-	-	
F13	Detergent use	number of population (3897) (CBS, 2014)	10%	0.62 kgP/cap (Van Drecht et al., 2009)	25%
F14	Imported detergent	number of population (3897) (CBS, 2014)	10%	0.62 kgP/cap (Van Drecht et al., 2009)	25%
F15	Greywater	number of population (3897) (CBS, 2014)	10%	0.62 kgP/cap (Van Drecht et al., 2009)	25%
F16	Kitchen waste	Kitchen waste (39.3 kg/cap per year) (DEI, 2014)	10%	Dry matter content (40%) (Eggleston et al., 2006), N content (3.16%), and P content (0.52%) (Zhang et al., 2007)	25%
F17	Blackwater	-	-	-	-
F18	Liquid fraction of soakage pit	-	-	Transfer coefficient in liquid fraction of soakage pit for N (82%), and for P (71%) (Montangero and Belevi, 2007)	10%

Flow	Description	Mass flow & N and P content			
		Mass flow	**CV mass flow**	**N and P content**	**CV N and P content**
F19	N-gas emission of soakage pit	-	-	-	-
F20	Leachate	-	-	Transfer coefficient of N in leachate (24%) (Wang et al., 2014), No P leaching is assumed	25%
F21	N-gas emission of landfill	-	-	Transfer coefficient of N-gas emission (20.5%) (Onay and Pohland, 1998)	25%
F22	Imported fertilizer	Fertilizer rate (833 kg/ha) (Hazel, 2014).	50%	NPK (13:13:13) to fertilize 3.6 ha	0
F23	Atmospheric deposition	Total land area: 2109 ha (Smith et al., 2013)	10%	N deposition (0.75 kgN/ha per year)(Galloway et al., 2004); P deposition (0.05 kgP/ha per year) (Tipping et al., 2014)	25%
F24	N-gas emission of fertilizer and manure	-	-	Of the surplus, N is lost through ammonia emission (24%), soil denitrification (16%) (Sutton, 2013)	25%

Flow	Description	Mass flow & N and P content			
		Mass flow	CV mass flow	N and P content	CV N and P content
F25	Leaching/Run-off of N	-	-	Of the surplus, N is lost through leaching and runoff (60%) (Sutton, 2013)	25%
	Erosion/run-off of P	Total land area: 2109 ha (Smith et al., 2013)	10%	Average rate of P erosion in Dominica, St Lucia, and St. Vincent (0.134 kgP/ha per year) (McDowell, 1995), Ratio rainfall at St. Eustatius is half of the other islands.	25%
F26	Leaching	-	-	-	-

Table S1.3 Insert and reconciled value of N and P flows in St. Eustatius

Flow	Description	Insert value to STAN				Reconciled value in STAN			
		N flow (kgN/ year)	**N flow Uncertainty (%)**	**P flow (kgP/ year)**	**P flow Uncertainty (%)**	**N flow (kgN/ year)**	**N Uncertainty (%)**	**P flow (kgP/ year)**	**P Uncertainty (%)**
F1	Crop uptake	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN	21,123	13	4217	14
F2	Vegetable products	46	54	7	54	46	54	7	54
F3	Local feed	21,077	13	4,210	14	21,077	13	4,210	14
F4	Imported feed	2,181	13	422	14	2,181	13	422	14
F5	Livestock for slaughter	1,449	26	413	26	1,449	26	413	26
F6	Exported animal product	595	29	215	28	595	29	215	28
F7	Slaughtered animal waste	685	34	183	35	685	34	183	35
F8	Biological nitrogen fixation	41,433	14	0	0	41,430	12	0	0

Flow	Description	Insert value to STAN				Reconciled value in STAN			
		N flow (kgN/year)	N flow Uncertainty (%)	P flow (kgP/ year)	P flow Uncertainty (%)	N flow (kgN/ year)	N Uncertainty (%)	P flow (kgP/ year)	P Uncertainty (%)
F9	Manure	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN	21,809	13	4,219	14
F10	Food	18,101	14	2,102	14	18,101	14	2,102	14
F11	Market waste	1,826	27	301	27	1,826	27	301	27
F12	Imported food	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN	19,712	13	2,381	19
F13	Detergent use	0	0	783	27	0	0	783	27
F14	Imported detergent	0	0	Calculated in STAN	Calculated in STAN	0	0	783	27
F15	Greywater	0	0	Calculated in STAN	Calculated in STAN	0	0	783	27
F16	Kitchen waste	2,033	27	335	27	2,033	27	335	27

Flow	Description	Insert value to STAN				Reconciled value in STAN			
		N flow (kgN/year)	**N flow Uncertainty (%)**	**P flow (kgP/ year)**	**P flow Uncert ainty (%)**	**N flow (kgN/ year)**	**N Uncert ainty (%)**	**P flow (kgP/ year)**	**P Uncert ainty (%)**
F17	Blackwater	Calculated in STAN	Calculated in STAN	Calculate d in STAN	Calcula ted in STAN	16,068	16	1,767	24
F18	Liquid fraction of soakage pit	13,175	19	1,255	24	13,175	19	1,255	24
F19	N-gas emission of soakage pit	0	0	0	0	0	0	0	0
F20	Leachate	1,091	14	0	0	1,091	14	0	0
F21	N-gas emission of landfill	932	29	0	0	932	29	0	0
F22	Imported fertilizer	390	50	170	50	390	50	170	50
F23	Atmospheric deposition	1,591	27	105	25	1,591	27	105	25
F24	N-gas emission of fertilizer and manure	17,636	16	0	0	17,637	15	0	0

Flow	Description	Insert value to STAN				Reconciled value in STAN			
		N flow (kgN/ year)	**N flow Uncertainty (%)**	**P flow (kgP/ year)**	**P flow Uncertainty (%)**	**N flow (kgN/ year)**	**N Uncertainty (%)**	**P flow (kgP/ year)**	**P Uncertainty (%)**
F25	Leaching/Run-off of N	26,454	30	0	0	26,460	19	0	0
	Erosion/run-off of P	0	0	141	27	0	0	141	27
F26	Leaching	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN	14,266	18	0	0

S2. Supplementary Material Chapter 3

S2.1 Sanitation concepts for comparison

In the supplementary materials section, the sanitation concepts selected for comparison are described in Table S2.1.

Table S2.1 Sanitation concepts selected for comparison with different application of technologies varying from collection, wastewater treatment, and reuse.

Concept	Collection	BW treatment	GW treatment	KW treatment	Reuse
1	BW and GW treated at household level	ST (3 PE) at household level, BW effluent transported via small bore sewer system to a TF (775 PE) at community level	CW (3 PE) at household level	KW and BW sludge co composting, BW sludge collected 1-2 year	BW effluent, compost
2	BW and GW collected at household level	UASB-ST (3 PE) at household level, BW effluent transported via small bore sewer system to a TF (775 PE) at community level	CW (3 PE) at household level	KW and BW sludge co composting, BW sludge collected 1-2 year	BW effluent, Compost, Energy

Concept	Collection	BW treatment	GW treatment	KW treatment	Reuse
3	BW collected at community level, transported via conventional gravity sewer, GW collected at household level	UASB (775 PE) at community level for BW treatment, BW effluent transported to a TF (775 PE) at community level	CW (3 PE) at household level	KW and BW sludge co composting, BW sludge collected 1-2 year	BW effluent, Compost, Energy
4	BW and GW collected and treated at centralized level, transported via conventional gravity sewer	UASB+TF (3877 PE) at centralized level	UASB+TF (3877 PE) at centralized level	KW and sludge co composting, BW sludge collected 1-2 year	BW and GW effluent, compost
5	BW and GW collected and treated at centralized level, transported via conventional gravity sewer	CAS+N/P removal (3877 PE) at centralized level	CAS+N/P removal (3877 PE) at centralized level	KW and sludge co composting, BW sludge collected 1-2 year	BW and GW effluent, compost

The common features of the selected sanitation treatment technologies are:

- UASB or UASB septic tanks (UASB-ST) for BW treatment – These treatment technologies have been selected because the study area is located in tropical climates, which provide favourable conditions for energy efficient anaerobic conversion of the organic matter of BW (Wiegant, 2001, Kujawa-Roeleveld et al., 2005, Luostarinen et al., 2007). UASB-ST is an improved version of a ST for energy recovery and better removal of COD (Lettinga et al., 1993, Kujawa-Roeleveld et al., 2005).
- Trickling Filter (TF) as a post treatment – In all cases, except for CAS application, post-treatment of the effluent is applied, as the anaerobically treated BW and mixed domestic wastewater contain pathogens and remaining organic matter (Chernicharo, 2006, Tervahauta et al., 2013). TFs have very little or even no energy consumption, are robust, and simple in terms of equipment, design, operation and maintenance compared to other post treatment technologies, such as Constructed Wetland (CW) or polishing ponds (Chernicharo, 2006, Chernicharo and Almeida, 2011).
- Sewer systems: Small bore sewers and gravity sewers – A small bore sewer system is a solid-free sewer with a small diameter (minimum 100 mm) and therefore, lower costs for installation (i.e. lower trenching) (Otis and Mara, 1985, Nawrot, 2010). This sewer system is selected to transport the effluent of ST or UASB-ST. A gravity sewer is selected to transport BW to a communal UASB. Likewise, for the transport of mixed BW and GW to the centralized UASB reactor or CAS system gravity sewerage and pumping stations are applied.
- Constructed wetland (CW) as GW treatment – This has been selected as the main treatment due to ease of construction and low costs for operation and maintenance (Kivaisi, 2001). For this study, vertical flow sub-surface CW is preferred over a horizontal flow sub-surface CW due to better removal of pollutants and low space requirement (Avery et al., 2007, Ghunmi et al., 2011).
- Composting as treatment of produced sludge – Sludge from the treatment is co-composted with KW. Composting is selected as it is simple and relies on natural process for pathogens removal (Strauss et al., 2003, Oarga Mulec et al., 2016). KW is chosen as a co-composting substrate to increase the biodegradable COD content. The type of composting is open windrow with mechanised system for the substrate mixing.

- Recovery products – Water, nutrients, energy (biogas), and organic matter (compost) are products for reuse. The biogas produced during the anaerobic treatment is applied as an energy source for lighting or cooking (Chen et al., 2012).

S2.2 Selected Sustainability Indicators

Table S1.3 Selected sustainability indicators for comparison

Category	**Indicator**	**Criteria for Evaluation**
Environmental	1. Energy use	• Net energy use (consumption-production) (kJ/cap per day)
	2. Nutrient recovery/reuse a. N recovery/reuse b. P recovery/reuse	• N in the effluent and compost that can be reused (gTN/cap per day) • P in the effluent and compost (gTP/cap per day)
	3. BOD/COD a. BOD in the effluent b. COD in the effluent	• BOD in the effluent (gBOD/cap per day) • COD in the effluent (gCOD/cap per day)
	4. Pathogens	• The amount of pathogens in the effluent (CFU/100 ml)
	5. GHG emission	• The amount of GHG emission (kgCO_2-eq/cap per day)
	6. Land area requirement	• Total land area required to construct the treatment plant (m^2/cap)

Category	Indicator	Criteria for Evaluation
Economic	7. Capital expenditure (CAPEX)	• Total costs required for sewer, treatment system, and land use (Euro/cap per year).
	8. Operational expenditure (OPEX)	• Total costs required to operate the sanitation concept per year (Euro/cap per year)
Social-cultural	9. Acceptance	• The level of odour problems of treatment system • Simplicity of operation of the treatment by end-users
	10. Competences and education required	• Ratio of skilled and non-skilled labours
Technological	11. Flexibility/ Adaptability	• Easiness in construction of the sewer and treatment system • Easiness of the sewer and treatment system to expand with a growing population
	12. Reliability/continuity of service	• The capacity of the system to respond to failures in the system (pipe blockage, power failures) • The impact of failures on society and the environment

S2.3 Removal efficiencies of sanitation treatment technologies.

Limited data and information on the performance of sanitation concepts suited to apply on St. Eustatius required an extensive literature research on the value of removal efficiency of each sanitation technology covered in this study. The main parameters for the design of sanitation treatment technologies are BOD, COD, TN, TP, TSS, and Pathogens (Faecal Coliforms). The removal efficiency refers to the capacity of the technology to remove organic matter (BOD and COD), to divert nutrients (especially TP) from the liquid phase to the sludge, and to remove pathogens from the liquid phase.

Technologies were selected based on the following criteria:

1. Maturity of the technology – The selected sanitation technology is preferably applied full-scale or pilot-scale. If there is no information on the application at full or pilot scale, lab-scale information is used.
2. Type of domestic wastewater treated: BW, GW, or mixed BW and GW.
3. Application in Latin America and Caribbean (LAC) countries. If there is no adequate information of application in LAC countries, information from applications in comparable regions is used.

Septic tank: Table A3 shows the reported removal efficiencies of ST treating BW or domestic wastewater (BW+GW) derived from different literature sources. In this study, the removal efficiencies of COD and BOD were based on the reported literature value treating BW only as ST on St. Eustatius is applied to treat the BW. The removal efficiency of COD is 89% and BOD is 93% (Lettinga et al., 1991). Values for nutrient removal efficiencies in ST are scarce in literature. In a ST, the majority of N and all P are in the effluent and a small part in the sludge; the division of N and P over the solid phase and liquid phase is derived from van Voorthuizen et al. (2008), applying UASB for BW. The reduction of N and P in the water fraction is regarded as removal efficiency, which is 14% for TN and 5% for TP. The value of FC removal efficiency is around 1 log, which is based on the reported value of ST treating BW (Kerstens et al., 2015).

UASB-ST: Table A4 shows various removal efficiencies of UASB-ST treating BW or domestic wastewater (BW+GW) as derived from literature. In the present study, the removal efficiency of BOD and COD is based on the average removal efficiencies for treatment of BW only (Lettinga et al., 1993, Kujawa-Roeleveld et al., 2005). The average removal efficiency of COD is 87% and BOD is 93%. These values are based on the measurement of full-scale application of a UASB-ST in Indonesia. Information on TN removal efficiency of UASB-ST is scarce, therefore in the present study TN and TP removal efficiencies are based on van Voorthuizen et al. (2008) and are 14% for TN and 5% for TP. The reported TP removal efficiency of 50% (Kujawa-Roeleveld and Zeeman, 2006) is not used (Table A2). It is relatively high due to the application of a vacuum toilet and can be explained by the high concentration of TP in the BW (de Graaff et al., 2010). The removal efficiency of FC is 3 log, which is based on the reported value of Kujawa-Roeleveld et al. (2005).

UASB: Table A5 shows the various removal efficiencies of UASB treating BW or domestic wastewater (BW+GW) reported in literature. For a UASB treating BW, the removal efficiency is based on the average data from de Graaff et al. (2010), van Voorthuizen et al. (2008), and Hernandez-Leal et al. (2017) and is 78% for COD. These data are from long-term monitoring of UASB treating BW in the Netherlands at temperatures similar to LAC countries both at laboratory and full scale. For BOD, an equal removal efficiency is assumed as for COD. Hernandez-Leal et al. (2017) reported the performance of a UASB treating (vacuum collected) BW and KW of 79 people, while it is designed for 1200 people. Therefore, COD removal efficiencies might be overestimated while TN removal efficiency might be underestimated. As with ST and UASB-ST, TN and TP removal efficiencies are based on van Voorthuizen et al. (2008). No differences for UASB treating BW and GW are assumed in comparison with UASB treating BW only. The removal efficiency of FC is 3 log, which is based on UASB-ST (Kujawa-Roeleveld et al., 2005) since there is no information on FC removal efficiency of UASB alone.

For UASB treating domestic wastewater (BW+GW), many experiences are recorded in the literature. UASB has been applied in Brazil at full-scale and pilot-scale. The BOD and COD removal efficiencies are based on average literature values (Chernicharo and Nascimento, 2001, De Almeida et al., 2009, Pontes and Chernicharo, 2011, Almeida et al., 2013). The removal efficiency of BOD is 73% and COD is 69%. For a UASB treating BW and GW, literature values of van Voorthuizen et al. (2008) are used for TN and TP removal efficiencies, and Kujawa-Roeleveld et al. (2005) for the FC removal efficiency.

TF: Table A6 shows the various removal efficiencies of TF treating effluent of a UASB. The removal efficiencies of COD and BOD used in the present study are the average values of reported literatures (Chernicharo and Nascimento, 2001, De Almeida et al., 2009, Pontes and Chernicharo, 2011, Almeida et al., 2013) and are 44% for COD and 56% for BOD. The removal efficiency of TN is 15% Almeida et al. (2013). According to da Costa et al. (2016), there is hardly or very limited TP removed during the treatment in TF. Hence, the removal efficiency of TP is 0. The removal efficiency of pathogens (coliforms) in TF is around 1.3 log, which is based on the reported value of Tawfik et al. (2006).

CAS+N/P removal: Data for CAS+N/P removal is based on the average values given by RIONED (2009) which reported that the removal efficiency of BOD is 98%, COD is 92%, TN is 80%, TP is 82%, and FC is 4 log. Although the study is for the case of the Netherlands, the values were adopted for the context of St. Eustatius. If the CAS system with N/P removal is properly designed for the context of a tropical region, the CAS system for the removal of organic matter (BOD and COD) and nutrients (TN and TP) will operate vigorously (pers.comm with Hardy Temmink).

CW: Table A7 shows the removal efficiency of a vertical flow CW treating greywater. Focus is limited to vertical flow CW as these have better removal efficiencies and lower space requirements compared to horizontal sub-surface flow CW. The removal efficiencies of CW on BOD and COD are based on average literature data (Paulo et al., 2009; Avery et al., 2007; Gross et al., 2007). The removal efficiency of BOD is 79% and COD is 93%. TN and TP removal efficiencies are based on reported values of Paulo et al. (2009), Paulo et al. (2013) and Gross et al. (2007). Since there is limited information on FC removal efficiency of vertical CW treating GW, the value is based on the reported data of Avery et al. (2007).

Composting facility: Since the function of the composting facility is to stabilize organic matter of the generated sludge and kitchen waste, the removal efficiency of this technology is not included in the assessment. The calculation of compost produced in each sanitation concept is described in section 4.

Table S2.8 gives an overview of the removal efficiency of each technology in each sanitation concept, as based on Tables S2.3 to S2.7

Table S2.3 Removal efficiency of ST treating BW or BW+GW

Source[1]	Location	Wastewater streams	HRT (day)	OLR (kg COD/m3.day)	Removal Efficiency					
					COD	BOD	TSS	TN	TP	FC
1	Indonesia; Full-scale house	BW	15	0.39	89%	93%	92%			
2	Brazil; advanced ST (3 consecutive ST)	BW	20	0.047	79-86%	85-92%				
3	Brazil; Full-scale house	BW + GW	2	0.34	70-75%					
Used in the present study		BW	n.a	n.a	84%[a]	89%[a]	n.a	14%b	5%[b]	1 log[c]

[1] **Sources:** 1 : (Lettinga et al., 1991); 2: (EMBRAPA, 2017); 3: (Chernicharo, 2006)
[a] BOD and COD removal are based on the average value of Lettinga et al. (1991) and EMBRAPA (2017)
[b] TN and TP removal are based on van Voorthuizen et al. (2008), see text.
[c] FC removal is based on the assumption used in the application of ST treating BW in a developing country (Kerstens et al., 2015).

Table S2.4 Removal efficiency of UASB-ST treating BW or BW+GW

Source[1]	Location	Wastewater streams	HRT (day)	OLR (kg COD/m3.day)	Removal Efficiency					
					COD	**BOD**	**TSS**	**TN**	**TP**	**FC**
1	Indonesia; Full-scale house (>20°C)	BW	15	0.37	90-93%	92-95%	93-97%			
2	Netherlands; Pilot-scale (25°C)	BW	29	0.42	78%				50%	3 log
1	Indonesia; Full-scale house (>20°C)	BW + GW	1.4	0.96	67-77%	82%	74-81%			
Used in the present study		BW	n.a	n.a	92%[a]	93%[a]	n.a	14%[b]	5%[b]	3 log[c]

[1]**Sources: 1:** (Lettinga et al., 1993); 2: (Kujawa-Roeleveld et al., 2005)
[a] BOD and COD removal are based on Lettinga et al. (1993).
[b] TN and TP removal are based on van Voorthuizen et al. (2008).
[c] FC removal is based on Kujawa et al. (2005).

Table S2.5 Removal efficiency of UASB treating BW or BW+GW

Source[1]	**Location**	**Wastewater streams**	**HRT (day)**	**OLR (kg COD/m3.day)**	**Removal Efficiency**					
					COD	**BOD**	**TSS**	**TN**	**TP**	**FC**
1	Netherlands, Lab-scale (25°C)	BW-vacuum toilet	8.70	1	78%			9%	40%	
2	Netherlands, Lab-scale (37°C)	BW-flush toilet	0.50	2.3	64%			14%	5%	
3	Netherlands , Full-scale (35°C)	BW+KW	34	0.28	92%			4%	22%	
4	Brazil; Full-scale house (Tropic)	BW+GW	0.50	0.34	75-80%		70-75%			
5	Brazil; Pilot-scale (Tropic)	BW+GW	0.17	0.94-4.0	65-79%	58-81%	49-78%			

Source[1]	Location	Wastewater streams	HRT (day)	OLR (kg COD/m3.day)	Removal Efficiency					
					COD	BOD	TSS	TN	TP	FC
6	Brazil; Full-scale (20 to 25ºC)	BW+GW	0.35	1.50	66%	79%	72%			
6	Brazil; Full-scale (20 to 25ºC)	BW+GW	0.32	0.94	65%	68%	70%			
7	Brazil; Pilot scale (23ºC)	BW+GW	0.32	1.53	59%	72%	63%			
8	Brazil	BW+GW	0.38	1.2	50–70%	75%	70-80%			
Used in the present study		BW	n.a	n.a	78%[a]	78%[a]	n.a	14%[c]	5%[c]	3 log[d]
Used in the present study		BW+GW	n.a	n.a	69%[b]	73%[b]	n.a	14%[c]	5%[c]	3 log[d]

[1]**Sources: 1:** (de Graaff et al., 2010); 2: (van Voorthuizen et al., 2008) ; 3: (Hernández Leal et al., 2017) 4: (Coelho et al., 2004); 5: (Chernicharo and Nascimento, 2001); 6: (De Almeida et al., 2009); 7: (Pontes and Chernicharo, 2011); 8: (Almeida et al., 2013)

[a] BOD and COD removal are based on the average data from de Graaff et al. (2010), van Voorthuizen et al. (2008), and Hernandez-Leal et al. (2017), see text.

[b] BOD and COD removal are based on the average data from Chernicharo and Nascimento (2001), De Almeida et al., (2009), Pontes and Chernicharo (2011), and Almeida et al. (2013).

[c] TN and TP removal efficiencies are based on van Voorthuizen et al. (2008), see text.

[d] FC removal efficiency is based on the assumption used in the application of UASB-ST (Kujawa-Roeleveld et al., 2005).

Table S2.6 Removal efficiency of TF treating anaerobically treated effluent of UASB

Source[1]	Location	Wastewater streams	HRT (day)	OLR (kg COD/m3.day)	Removal Efficiency					
					COD	BOD	TSS	TN	TP	FC
1	Brazil; Pilot-scale (Tropic)	UASB, Rotosponge	0.01-0.04	0.9-5.6	25-50%	33-67%				
2	Brazil; Pilot scale (23°C)	UASB, Slag	0.15	0.7	41%	52%	57%			
2	Brazil; Pilot scale (23°C)	UASB, Rotopack	0.12	1.45	48%	50%	67%			
2	Brazil; Pilot scale (23°C)	UASB, Rotosponge	0.12	1.45	56%	56%	69%			
3	Brazil; Pilot scale (23°C)	UASB, Rotosponge	0.41	1.2	47%	56%	53%			
4	Japan; Pilot scale (25°C)	UASB, sponge	0.08	2.49						1.3 log

Source[1]	Location	Wastewater streams	HRT (day)	OLR (kg COD/m3.day)	Removal Efficiency					
					COD	BOD	TSS	TN	TP	FC
5	Brazil: Pilot scale (22.1ºC)	UASB, sponge	0.29	0.5	28%				0	
6	Brazil: Pilot scale (23ºC)	UASB, Rotosponge	2	0.75	48%	50%	67%	15%		
Used in the present study			n.a	n.a	41%[a]	50%[a]	n.a	15%[b]	0[c]	1.3 log[d]

[1]**Sources:** 1: (Chernicharo and Nascimento, 2001); 2: (De Almeida et al., 2009) ; 3: (Pontes and Chernicharo, 2011); 4: (Tawfik et al., 2006); 5: (da Costa et al., 2015); 6 (Almeida et al., 2013)
[2] TF media is also given: Rotosponge, rotopack, and slag.
[a] BOD and COD removal are based on the average value of Chernicharo and Nascimento, (2001), De Almeida et al. (2009), Pontes and Chernicharo (2011), and Almeida et al. (2013).
[b] TN removal efficiency is based on Almeida et al. (2013).
[c] TP removal efficiency is based on da Costa et al. (2013).
[d] Pathogen efficiency is based on Tawfik et al. (2006)

Table S2.7 Removal of efficiency of CW treating GW. Only data for vertical sub-surface flow CW is given.

Source[1]	**Location**	**Wastewater streams**	**HRT (day)**	**OLR (kg COD/m3.day)**	**Removal Efficiency**					
					COD	**BOD**	**TSS**	**TN**	**TP**	**FC**
1	Brazil	GW	1.8-3.4		70-89%					
2	Brazil	GW			74%	86%		68%	60%	
3	UK	GW			80.90%	93.10%				4.8 log
4	UK	GW			81%	99.8%	98%	69%	71%	
Used in the present study			n.a	n.a	79%[a]	93%[a]	n.a	67%[b]	65%[b]	4.8 log[c]

[1]**Sources:** 1: (Paulo et al., 2013); 2: (Paulo et al., 2009); 3: (Avery et al., 2007); 4: (Gross et al., 2007)
[a] BOD and COD removal efficiencies are based on the average value of Paulo et al. (2009), Avery et al. (2007), and Gross et al. (2007).
[b] TN and TP removal efficiencies are based on the average value of Paulo et al. (2009), and Gross et al. (2007).

Table S2.8 The removal efficiency of wastewater constituents in each sanitation concept

Parameter	**Concept 1**				**Concept 2**			
	BW			**GW**	**BW**			**GW**
	ST	**TF**	**ST+TF**	**CW**	**UASB-ST**	**TF**	**UASB-ST+TF**	**CW**
BOD	89%	50%	95%	93%	93%	50%	97%	93%
COD	84%	41%	91%	79%	92%	41%	95%	79%
TN	14%	15%	27%	67%	14%	15%	27%	67%
TP	5%	0%	5%	65%	5%	0%	5%	65%
Coliforms	1 log	1.3 log	2 log	4.8 log	3 log	1.3 log	4 log	4.8 log

Parameter	**Concept 3**				**Concept 4**			**Concept 5**
	BW			**GW**	**BW + GW**			**BW+GW**
	UASB	**TF**	**UASB+TF**	**CW**	**UASB**	**TF**	**UASB+TF**	**CAS+N/P removal**
BOD	93%	50%	97%	93%	73%	50%	87%	98%
COD	92%	41%	95%	79%	69%	41%	82%	92%
TN	14%	15%	27%	67%	14%	15%	27%	80%
TP	5%	0%	5%	65%	5%	0%	5%	82%
Coliforms	3 log	1.3 log	4 log	4.8 log	3 log	1.3 log	4 log	4 log

S2.4 Sludge and compost production

The sludge production in ST, UASB-ST, and UASB was calculated according to Metcalf et al. (2003) (Equation 2):

$$P = \frac{Q(COD_{SS,in} - COD_{SS,ef}) * (1 - \eta_h)}{X} \quad (2)$$

where P is the sludge production (m^3/cap.d), Q is the influent flow (m^3/cap/d), $COD_{SS,in}$ is the influent CODss (g/m^3), $COD_{SS,ef}$ is the effluent concentration (g/m^3), in the effluent $COD_{SS,ef}$ (g/m^3), η_h is the fraction solids hydrolysed, and X is the COD_{SS} concentration in the sludge (g/m^3). $COD_{SS,in}$ and $COD_{SS,ef}$ was calculated based on the CODtotal/CODss ratio of 0.76 (Kujawa-Roeleveld et al., 2005), and COD_{SS} removal efficiency of ST (0.6), UASB-ST (0.85), and UASB (0.85) (de Graaff et al., 2011). Fraction of solids hydrolysed (η_h) applied in this study is 0.7 (Kujawa-Roeleveld et al., 2005).

The sludge production in the CAS system was calculated according to Metcalf et al. (2003) (Equation 3):

$$S = Y * Q * (BODin - BODef) \quad (3)$$

where S is the sludge production of CAS (kgVSS/d), Y is the sludge yield (kgVSS/kg BODremoved), Q is the influent flow (m^3/cap.d), BODin is the influent BOD concentration (kg/m^3) and BODef is the effluent BOD concentration (kg/m^3). A sludge yield of 0.58 kgVSS/kg BODremoved was used for the AS process (SRT 12 d). The sludge production as total solids was calculated using a VSS/TSS ratio of 0.85 (Tchobanoglous and Stensel, 2004). The total wet sludge production was calculated using a dry solid content of 2.5%.

The compost production was calculated based on the co-composting of substrate of KW (m^3/cap.day) and generated sludge (m^3/cap.day) in each sanitation concept (Equation 4). The sludge is dewatered prior to the co-composting process by means of evaporation on sludge drying beds.

Compost production (m^3/cap.day) =

$(V_{sludge}*TS_{sludge} + V_{KW}*TS_{KW}) * (1\text{-VS/TS ratio}) + (V_{sludge}*TS_{sludge} + V_{KW}*TS_{KW}) * (\text{VS/TS ratio}) * (1\text{-Biodegradability}) + \text{Water content of compost}$ (4)

where TS_{KW} is 40%, TS_{sludge} is 20%, VS/TS ratio is 65% (Kerstens et al., 2015), and biodegradability is 70%. Water content was calculated based on the difference between the water production and evaporation during composting process. The applied heat production is 20 MJ/kg O_2 or 26.52 MJ/m^3 O_2 (at 1atm) and 40% of heat is used to evaporate produced water.

During composting process of KW and sludge, N is lost to the atmosphere and leaching in the range of 35-75%. For the present study, 55% of TN in the KW and sludge is lost, hence 45% of TN remains in the compost. For TP content, it was calculated based on the TP in the sludge and KW.

S2.5 Land requirements of selected sanitation technologies

OLR is the main parameter used to estimate the total land area required for sanitation technologies in concepts 1 to 5. The OLR of each technological treatment (Table A9) has been estimated based on literature values. The OLR of ST (0.34 kgCOD/m^3/d) was estimated using the literature value reported in van Buuren (2010). The OLR of UASB-ST (0.42 kgCOD/m^3/d) was estimated using the value reported in Kujawa-Roeleveld et al. (2005). The OLR of UASB (1.3 kgCOD/m^3/d) treating BW was estimated using the literature value of de Graaf et al. (2010). The value is for the UASB treating BW and GW, the value of van Lier et al.(2010) was used. The value is in the range of 1.15-1.45 kgCOD/m^3/d. Hence, in the present study, the OLR of UASB treating BW and GW is 1.3 kgCOD/m^3/d. The OLR of TF is based on the average literatures indicated in Table A6. The OLR of TF is 1.11 kgCOD/m^3/d.

Table A9. OLR selected for ST, UASB, UASB-ST and TF applied in concept 1, 2, 3, and 4.

Parameter	Concept 1		Concept 2		Concept 3		Concept 4	
	Main treatment	Post-treatment	Main treatment	Post-treatment	Main treatment	Post-treatment	Main treatment	Post-treatment
	ST	TF	UASB -ST	TF	UASB	TF	UASB	TF
OLR (kgCOD/ m^3 per day)	0.34[1]	1.11[2]	0.42[3]	1.11[2]	1.3[4]	1.11[2]	1.3[4]	1.11[2]

[1](van Buuren, 2010)
[2](Kujawa-Roeleveld et al., 2005)
[3](de Graaff et al., 2010)
[4](van Lier and Huibers, 2010)

The volume required of ST, UASB, UASB-ST, and TF is calculated according to Equation 5. The total area required (m^2) was calculated from the volume and an assumed height of the reactor. The height of UASB and UASB-ST is in the range 3-5 m, while the height of TF is around 1.8-2.4 m (Metcalf et al., 2003). The height of ST is 2.1 m (Philippi et al., 1999).

$$V = \frac{COD_{in} * Q}{OLR} \quad (5)$$

Where: V=volume of reactor (m^3/cap), CODin=COD_{total} influent (kg/m^3), Q=flow of wastewater (m^3/cap per day), and OLR=Organic Loading Rate (kgCOD/m^3 per day).

For concept 5, the total area required is calculated based on Tervahauta et al. (2013). The total land area of concept 5 (application of Conventional Activated Sludge) consists of biological reactors and secondary settling tank.

Since the sludge produced in all sanitation concepts (1 – 5) is co-composted with organic wastes (kitchen waste), the total land area includes the area required for dewatering and composting processes. The total area is calculated based on the total volume of sludge and organic wastes over the expected height of the composting pile (2 meters). The composting process is expected for 60 days.

The total area required for CW is calculated based on the equation proposed by Kickuth (UN-HABITAT, 2008) (Equation 6).

$$A = \frac{Q*(lnC_i - lnC_e)}{K_{BOD}} \quad (6)$$

Where: A = Surface area of bed (m^2), Q = average daily flow rate of greywater (m^3/d), C_i = BOD concentration in the influent (mg/l), C_e = BOD concentration in the effluent (mg/l), K_{BOD} = rate constant (m/d), and K_{BOD} for VSSF-CW= 0.32 m/d. The height of vertical CW is assumed to be 1.5 m.

S2.6 Sewer systems and sewer costs estimation

Potential locations for community-on-site treatment were pre-selected to design sewer systems. There were five potential locations identified based on observations of elevation and density of the residential buildings on the island during field work on St. Eustatius in 2015 and 2016. With the help of satellite images, the total area and perimeter was estimated (Figure S2.1). To simplify calculations, the total urban area of 191 ha (Smith et al., 2013, Firmansyah et al., 2017) was divided into five similar urban areas of 38.2 ha per community on St. Eustatius. Assuming a square shape, the length and width of each area is 1.095 km x 1.095 km.

Figure S2.1 Selection of five potential locations for community-on-site treatment on St. Eustatius

The length of the sewer was calculated using the generic Urban Water Infrastructure Model (UWIM) (Equation 7 and 8) (Maurer et al., 2013). Sewer lengths within the community are calculated as follows:

$$L_{S,pub} = \left(\sqrt{\frac{A}{f1}} - \sqrt{\frac{1}{f2 \cdot \rho}}\right) \cdot \sqrt{\frac{f_1 \cdot A \cdot \rho}{4 \cdot f_2}} + \sqrt{f_1 + A} \quad (7)$$

$$L_{S,priv} = 0.5 \cdot A\sqrt{f_1 \cdot \rho} \quad (8)$$

where: $L_{S,pub}$ = Length of public sewer (m) and $L_{S,priv}$ = Length of private sewer (m); A = size of the area (m^2); ρ = building density (1.10^{-4} m^{-2}); f_1 = form factor of the area (2) and f_2 = form factor of a housing plot (0.5).

Small bore sewer system

A PVC small bore sewer system with a diameter of 100 mm was selected to transport anaerobically treated effluent when house-on-site STs or UASB-STs are applied (concept 1 and 2). This type of sewer is typically laid on the shallower ground and applied in LAC countries for wastewater flows below 80 litres/capita per day (Mara, 1996, Mara et al., 2007). For the context of ST. Eustatius, the ST and UASB-ST are used to treat BW with an average flow of 34 litres/cap per day. The investment cost of small bore sewer systems was based on the typical price in LAC countries in which 120-140 EUR per person is required for the installation of the sewer (Vargas-Ramírez and Lampoglia, 2006). This price includes the material costs and labour costs to install the sewer. The OPEX of small bore sewer system is related to the frequency of cleaning the piping system. It was estimated that 17% of the Capital Expenditures (CAPEX) is required for the maintenance of a community sewer system (Kerstens et al., 2015).

Conventional sewerage system

Concept 3 applies a gravity sewer to transport BW to a community-on-site UASB. For concept 4 and 5, the conventional sewerage consists of pressurised sewer and gravity sewer is required to transport mixed stream of BW and GW to a centralized treatment plant.

The diameter of the gravity sewer is calculated based on the Manning-Strickler equation for a circular channel flowing full (Equation 9) (Maurer et al., 2013)

$$Q_{full} = v_{full} * \frac{\pi}{4} * D \qquad (9)$$

Where, Q_{full}=total flow of wastewater streams (BW only or mixed BW and GW) (m/s), v_{full}=max. flow velocity (m/s), n=Manning-Strickler coefficient (empirically determined, 0.01m$^{1/3}$/s), and S=slope of the pipe (set at 0.001 m/m). Options for pipe diameters for gravity sewers are 110 mm, 200 mm, 300 mm or 400 mm. In this study, diameter of gravity sewer of 200 mm was selected to transport the BW stream, while 300 mm of gravity sewer was selected to transport mixed BW and GW.

For the pressurised sewerage system the hydraulic diameter of a sewer pipe is given by the transformed Darcy-Weisbach equation (Equation 10):

$$D = \left(\frac{0.8026 * f * L * Q_{\max}^{2}}{\Delta H}\right)^{1/5} \qquad (10)$$

Where, D= hydraulic diameter of the pressure pipe (m), f=Darcy friction factor (0.02), L=length of pipe (m), ΔH the friction factor (7 m), and Q_{max}=Total flow of wastewater streams (BW and GW). As in practice pressure pipes are available in 70 mm, 90 mm,110 mm,150 mm, 200 mm, 250 mm, 315mm, 350 mm, and 400 mm diameters, the dimension diameter > D was selected (200 mm).

Costs for the conventional sewerage system (pressurized sewer and gravity sewer) are calculated based on (Equation 11) (Roefs et al., 2017). The costs are determined as a function of pipe diameter.

$$CGS = Basic_{sewer} * 1.3^{\frac{diameter-300}{120}} \qquad (11)$$

Where CGS = Investment cost of Gravity Sewer [€/m], $Basic_{sewer}$ = € 130 (basic price per metre for diameter 300 mm), diameter = 110 mm (small bore sewer system), 200 mm (blackwater only), 300 mm (mixed blackwater and greywater). Pipe material is unreinforced concrete. The calculated costs are average costs for laying of new pipes in undeveloped areas in the Netherlands (RIONED, 2007). For gravity sewer a manhole needs to be installed for every 40 metres of piping. The empirical cost function is (Equation 12):

$$CM = 0.5 \times Basic_{manhole} * 2.718^{diameter \times 0.00231} \qquad (12)$$

Where CM = Investment cost of Manhole [€], $Basic_{manhole}$ = € 1940 (basic price per manhole for diameter pipe 300 mm and manhole dimensions 800x800x1400), diameter = 110 mm, 200 mm, 300 mm, 400 mm or 500 mm (RIONED, 2007).

Cost for pressurized sewer system (CPS) is calculated as follows:

$$CPS(150-400mm) = diameter\ (mm) * 0.61 * 1.1 \qquad (13)$$

Costs for construction of the pumping station consist out of costs for mechanical & electrical works and costs for constructing the building (RIONED, 2007):

$$CP_{mech\&elec} = 0.123 \times Basic_{mech\&elec} \times {Q_{max}}^{0.46} \qquad (14)$$

Where $CP_{mech\&elec}$ = Investment cost of Pump for mechanical and electrical works [€], $Basic_{mech\&elec}$ = € 35000 (basic price for mechanical & electrical works for pumping station with a capacity of approx. 100 m^3/h) and Q_{max} = maximum wastewater discharge [m^3/h]. Remaining values in the formula are empirically determined (RIONED, 2007). Costs for constructing the building of the pumping station are given by:

$$CP_{build} = 0.2 \times Basic_{build} \times {Q_{max}}^{0.35} \quad (15)$$

Where CP_{build} = Investment cost of Pump for building (with pump capacity between 50-200 m^3/h) [€], $Basic_{build}$ = € 48000 (basic price for constructing the building of a pumping station with a capacity of approx. 100 m^3/h) and Q_{max} = maximum wastewater discharge [m^3/h]. Remaining values in the formula are empirically determined (RIONED, 2007).

The operational costs of the sewerage systems are mainly incurred by pumping and cleaning of the pipes. Replacement of pipes is not taken into account in our model. The operation expenses for pumping stations comprise the maintenance of the pumping station and costs for electricity for pumping the wastewater. Yearly maintenance of the pumping station is given by 5 % of $CP_{mech\&elec}$ and 2.5 % of CP_{build} (RIONED, 2007). Electricity costs for pumping the wastewater are calculated by:

$$OP_{electricity} = \frac{Q_{year}}{Q_{max}} \times Power \times Costs_{electricity} \quad (16)$$

Where $OP_{electricity}$ = OPEX Pump for electricity [€], Q_{year} = yearly wastewater discharge [m^3/year], Q_{max} = maximum wastewater discharge [m^3/h], Power = 10 [kW] (electrical power of pumping station with wet sump installation, capacity 60-150 m^3/h), $Costs_{electricity}$ = 0.1 [€/kWh]. Yearly total OPEX for pumping station is then calculated by:

$$TOP = CP_{mech\&elec} \times 5\% + CP_{build} \times 2.5\% + OP_{electricity} \quad (17)$$

Where TOP = Total OPEX Pumping station [€/year].

Maintenance of sewer pipes is mainly related to cleansing, commonly by high pressure cleansing. Cleansing of the sewer is required before sewer inspection is possible. Sewer inspection frequencies and therefore sewer cleansing frequencies are in the order of 1/10 years (Ten Veldhuis, 2010) . Costs are depending on the quantity of pollution and the diameter of the pipe (RIONED, 2007):

$$OGC = 6.15 * 10^{-4} \times Basic_{cleansing} \times 2.718^{diameter \times 0.0017} \quad (18)$$

where: OGC = OPEX Gravity Sewer [€/m], $Basic_{cleansing}$ = € 1400 (basic price for cleansing per day), diameter = 200 mm, 300 mm or 400 mm. Remaining values in the formula are empirically determined (RIONED, 2007). The OGC does not include costs for processing sewer sand, which includes costs for sampling and analysing and for transportation. Average sewer sand pollution results in € 0.52 per metre discharge costs (diameter 300 mm, 8 kg sand per metre) (RIONED, 2007).

S2.7 Investment cost, CAPEX and OPEX of treatment system

For the UASB treating BW at community level and UASB treating BW and GW at centralized level, the estimation of the CAPEX was influenced by the flow rate, volume or dimension of the reactor, and gas processing unit. These include the piping costs, electrical and engineering costs, incompleteness and project costs. The OPEX incurred maintenance, energy costs, chemicals, staff, laboratory costs, and sludge processing unit. Chemicals and dewatering sludge process were not included as the use of chemicals is limited and dewatering sludge is based on evaporation.

The investment costs and OPEX of TF were based on the model of (Gratziou et al., 2006). The estimation is based on the treatment capacity per person equivalent (PE). Depending on the number of the PE, the TF have different calculated investment costs and OPEX. Since the TF is designed to treat COD influent of 500 mg/l, the cost of TF is adjusted based on the COD loading of anaerobic technologies (ST, UASB, and UASB-ST) in concept 1-5. For the TF treating effluent of BW at community level, the CAPEX of TF is 1049 EUR/cap, and OPEX is 52.89 EUR/cap. This is based on the assumption that the number of PE is 1000 people. Hence, there is a need for adjustment as the TF applied in the present study was designed to treat the effluent of UASB (775 PE). Moreover, there is a need to reduce the costs as it includes the sewerage costs. These have been calculated separately. For the TF treating BW and GW (with the capacity up to 5000 people), the CAPEX is 379 EUR/cap and OPEX is 13.75 EUR/cap. These values also need to be adjusted for the UASB treating BW and GW for 3877 people. For the application of ST and UASB-ST at household level, the typical CAPEX of ST is 230 EUR/household or per unit, and UASB-ST is 288 EUR/household per unit (van Buuren, 2010). The OPEX of these technologies include the emptying process of sludge, which was estimated 18-23 EUR/tank per two year (van Buuren, 2010). The costs information for vertical flow CW treating only GW at household level (concept 1, 2, 3 and 4) was estimated to be 133 EUR/m^2 (L. Rousseau et al., 2004), while OPEX for the vertical flow CW was estimated to be 9.1 EUR/m^2 per year (Nanninga, 2011). The investment cost of composting facilities was estimated based on the land use costs and the OPEX was based on the costs for turning the waste (US$46.4/ton) (Wei et al., 2001).

S2.8 Sensitivity Analysis

Table S2.10 Ranges of removal efficiencies applied in the sensitivity analysis.

Removal Efficiencies	**ST**	**UASB-ST**	**UASB (BW)**	**UASB (BW+GW)**	**CAS**	**TF**	**CW**
BOD	85%-93%	92%-95%	92%-95%	58%-81%	93%-94%	33%-67%	86%-99%
COD	79%-89%	90%-93%	90%-93%	65%-79%	97%-99%	25-56%	70%-89%
TN	±5%	±5%	±5%	±5%	±5%	±5%	±5%
TP	±1%	±1%	±1%	±1%	±1%	±1%	±1%
Pathogen	±10%	±10%	±10%	±10%	±10%	±10%	±10%
GHG emission							
N_2O Emission	0	0	0	0	0.00016 – 0.045	0.00016 – 0.045	±70%

Table S2.11 Ranges of qualitative indicators applied in the sensitivity analysis.

Qualitative Indicators	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**	**Concept 5**
Acceptance	2.75-4.25	2.5-4.00	3.00-4.25	3.00-5.00	4.00-5.00
Competences and education required	2.5-4.50	2.5-4.00	2.5-3.50	1.00-3.50	1.00-2.00
Flexibility/adaptability	3.75-5.00	3.38-4.83	3.25-4.17	2.5-4.00	2.5-3.50
Reliability/continuity of service	3.00-4.50	3.00-4.50	3.00-4.33	2.00-3.75	2.33-3.33

The results of the sensitivity analysis of selected parameters above have shown different effects for each sanitation concept (Table S2.12). A sanitation concept should have a minimum value (Min) for parameters: net energy use, COD in the effluent, Pathogen, GHG emission, CAPEX and OPEX. A concept will be the best if the frequency of the calculated values for Min indicators (less than the initial value) is more than 50%. TN and TP recovery and reuse, and qualitative indicators should have a maximum value (Max). If the frequency (more than the initial value) is more than 50%, a concept will have the best performance.

Based on the average values of Min and Max indicators (Table S2.12), more than 50% of the calculated values placed below initial value compared to other concepts. This means that the concept has the best performance for Min indicators. However, changing the Max indicators input variables has resulted in the lowest performance of Concept 4 because more than 50% of the calculated values is below initial values. In this conditions, Concept 3 has the best performance for Max indicators. The sensitivity analysis conducted indicates that the performance of sanitation concepts are affected by changing the input variables.

Table S2.12 Percentage of Monte Carlo runs above or below the initial values.

Category	Indicators	Max/Min	<= initial value					>initial value				
			Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Environmental	1. Net energy use (kJ/cap.year)	Min	N/A	36.0%	47.9%	67.9%	N/A	N/A	64.0%	52.1%	32.1%	N/A
	2. TN recovery/reuse (gTN/cap per day)	Max	50.2%	51.3%	48.4%	53.2%	49.2%	49.8%	48.7%	51.6%	46.8%	50.8%
	3. TP recovery/reuse (gTP/cap per day)	Max	50.7%	50.4%	48.5%	49.5%	52.0%	49.3%	49.6%	51.5%	50.5%	48.0%
	4. COD in the effluent (gCOD/cap per day)	Min	49.2%	49.5%	46.5%	51.6%	48.7%	50.8%	50.5%	53.5%	48.4%	51.3%
	5. Pathogen (CFU/100 ml)	Min	51.1%	46.4%	48.9%	50.5%	49.6%	48.9%	53.6%	51.1%	49.5%	50.4%
	6. GHG emission (kgCO2-eq/cap per year)	Min	38.7%	39.8%	37.3%	40.7%	39.5%	61.3%	60.2%	62.7%	59.3%	60.5%
Economic	7. CAPEX (EUR/cap per year)	Min	50.4%	51.9%	52.4%	49.0%	50.5%	49.6%	48.1%	47.6%	51.0%	49.5%
	8. OPEX (EUR/cap per year)	Min	50.4%	52.2%	48.8%	50.2%	50.1%	49.6%	47.8%	51.2%	49.8%	49.9%
Social-Cultural	9. Acceptance	Max	61.9%	57.1%	62.7%	74.4%	80.0%	38.1%	42.9%	37.3%	25.6%	20.0%
	10. Competences and education required	Max	54.4%	49.2%	49.0%	48.0%	50.9%	45.6%	50.8%	51.0%	52.0%	49.1%
Technological	11. Flexibility/adaptability	Max	50.4%	53.1%	53.0%	49.5%	49.8%	49.6%	46.9%	47.0%	50.5%	50.2%
	12. Reliability/continuity of service	Max	47.3%	50.2%	47.9%	50.3%	39.3%	52.7%	49.8%	52.1%	49.7%	60.7%
Average of Min Values			**48.0%**	**46.0%**	**47.0%**	**51.7%**	**47.7%**	**52.0%**	**54.0%**	**53.0%**	**48.4%**	**52.3%**
Average of Max Values			**52.5%**	**51.9%**	**51.6%**	**54.2%**	**53.5%**	**47.5%**	**48.1%**	**48.4%**	**45.9%**	**46.5%**

N/A : Not applicable as Concept 1 and Concept 5 do not have energy production.

S2.9 Detailed results of the evaluation of each sanitation technology per concept (Table S2.13-S2.17)

Table S2.13 Energy consumption, production and net energy use in each sanitation concept.

Parameter	**Technologies**	**Energy consumption (kJ/cap.d)**	**Energy production (kJ/cap.day)**	**Net energy (kJ/cap day)**
Concept 1	ST	0.49	-	0.49
	TF	-	-	-
	CW	-	-	-
	Composting	0.01	-	0.01
	Total	0.50	-	0.50
Concept 2	UASB-ST	0.69	424.59	-423.893
	TF	-	-	-
	CW	-	-	-
	Composting	0.01	-	0.008
	Total	0.70	424.59	-423.885
Concept 3	UASB	-	363.73	-363.73
	TF	-	-	-
	CW	-	-	-
	Composting	0.01	-	0.01
	Total	0.01	363.73	-363.72
Concept 4	UASB	197.26	559.55	-362.29
	TF	-	-	-
	Composting	0.01	-	0.01
	Total	197.27	559.55	-362.28

Parameter	**Technologies**	**Energy consumption (kJ/cap.d)**	**Energy production (kJ/cap.day)**	**Net energy (kJ/cap day)**
Concept 5	CAS+N/P removal	437.52	-	437.52
	Composting	0.02	-	0.02
	Total	437.53	-	437.53

[1] Energy production and consumption was calculated based on the methodology described in section 3.2.4.1

[2]Net energy use was calculated based on the difference between energy production and consumption

Table S2.14 Calculated effluent and compost (sludge+KW) quality of BOD, COD, TN and TP in each technology per sanitation concept.

Sanitation concepts	**Type of technology**	**Inflow[1] (m^3/cap per d)**	**BOD[2] (g/cap per d)**	**COD[2] (g/cap per d)**	**TN[2] (g/cap per d)**	**TP[2] (g/cap per d)**	**Coliforms (CFU/100 ml)**
Concept 1	ST (BW)	0.034	1.7	5.3	9.6	1.1	7 log
	TF (BW)	0.034	0.7	3.0	8.2	1.1	6 log
	CW (GW)	0.117	1.1	6.8	0.4	0.2	3 log
	Composting facility (Sludge+KW)	0.0003	ND	ND	4.4	0.3	ND
Concept 2	UASB-ST (BW)	0.034	1.7	3.8	9.6	1.1	5 log
	TF (BW)	0.034	0.7	2.2	8.2	1.1	4 log
	CW (GW)	0.117	1.1	6.8	0.4	0.2	3 log
	Composting facility (Sludge+KW)	0.0004	ND	ND	4.4	0.3	ND

Sanitation concepts	Type of technology	Inflow[1] (m^3/cap per d)	BOD[2] (g/cap per d)	COD[2] (g/cap per d)	TN[2] (g/cap per d)	TP[2] (g/cap per d)	Coliforms (CFU/100 ml)
Concept 3	UASB (BW)	0.034	5.3	10.6	9.6	1.1	5 log
	TF (BW)	0.034	2.3	5.9	8.2	1.1	4 log
	CW (GW)	0.117	1.1	6.8	0.4	0.2	3 log
	Composting facility (Sludge+KW)	0.0004	ND	ND	4.4	0.3	ND
Concept 4	UASB (BW+GW)	0.034	1.7	6.2	9.6	1.1	5 log
	TF (BW)	0.034	0.7	3.5	8.2	1.1	4 log
	Composting facility (Sludge+KW)	0.117	1.1	6.8	0.4	0.2	3 log

Sanitation concepts	**Type of technology**	**Inflow[1] (m^3/cap per d)**	**BOD[2] (g/cap per d)**	**COD[2] (g/cap per d)**	**TN[2] (g/cap per d)**	**TP[2] (g/cap per d)**	**Coliforms (CFU/100 ml)**
Concept 5	CAS+N/P removal (BW+GW)	0.0004	ND	ND	4.4	0.3	ND
	Composting facility (Sludge+KW)	0.151	10.7	24.7	10.7	1.6	5 log

Nd=Not defined
[1] The flow was calculated based on the generated wastewater (BW/GW) and Sludge+KW transporting to a composting facility
[2] BOD, COD, TN and TP was calculated based on the removal efficiency of each technology described in section 3 of Supplementary materials.

Table S2.15 Calculated GHG emission of each sanitation concept for comparison.

Parameter	Technologies	CH_4 emission ($kgCH_4$/cap.d)	N_2O emission (kgN_2O/cap.d)	CO_2 emission ($kgCO_2$/cap.d)	CO_2-eq emission ($kgCO_2$-eq/cap.d)
Concept 1	ST	0.0008	-	0.02057	0.03720
	TF	-	0.00024	-	0.07507
	CW	-	0.00000043	-	0.00013
	Composting	0.0008	0.000038	0.02190	0.05081
	Total	0.0016	0.000281	0.04247	0.16322
Concept 2	UASB-ST	0.0006	-	0.02057	0.03342
	TF	-	0.000242	-	0.07507
	CW	-	0.00000043	-	0.00013
	Composting	0.0017	0.000043	0.02208	0.07194
	Total	0.0023	0.000286	0.04265	0.18057
Concept 3	UASB	0.0006	-	-	0.01285
	TF	-	0.00024218	-	0.07507
	CW	-	0.00000043	-	0.00013
	Composting	0.0016	0.00005189	0.02239	0.07309
	Total	0.0023	0.00029450	0.02239	0.16116
Concept 4	UASB	0.0033	-	-	0.06976
	TF	-	0.000268	-	0.08312
	Composting	0.00246	0.000069	0.02299	0.09608
	Total	0.00578	0.000337	0.02299	0.24896
Concept 5	CAS+N/P removal	0.00720	0.000312	0.04232	0.29017

Parameter	Technologies	CH_4 emission ($kgCH_4$/cap.d)	N_2O emission (kgN_2O/cap.d)	CO_2 emission ($kgCO_2$/cap.d)	CO_2-eq emission ($kgCO_2$-eq/cap.d)
	Composting	0.005	0.000073	0.02312	0.16007
	Total	0.013	0.000385	0.06545	0.45024

[1]The emission of CH_4, N_2O, CO_2, and CO_2 equivalent was calculated based on the methodology described in section 2.4.3

Table S2.16 Calculated CAPEX and OPEX per capita for each sanitation technology per concept.

Concepts	Technologies	CAPEX				
		Sewerage system[1] (EUR/cap)	Treatment system[2] (EUR/cap)	Land use[3] (EUR/cap)	Total Investment (Euro)	Total CAPEX (Euro/cap. year)
1	ST	130	77	0.1	160224	6
	TF	0	683	0.1	529364	20
	CW	0	86	0.1	67054	3
	Composting	0	0	0.5	392	0
	Total	**130**	**846**	**0.8**	**757034**	29
2	UASB-ST	130	96	13	185449	7
	TF	0	683	0.1	529414	20
	CW	0	86	0.1	67054	3
	Composting	0	0	0.6	429	0
	Total	130	865	14.1	782346	30
3	UASB	184	263	0.6	171455	6
	TF	0	683	0.2	529488	20
	CW	0	86	0.1	67054	3
	Composting	0	0	0.6	491	0
	Total	184	1033	1.6	768488	29
4	UASB	340	348	1.1	1473321	11
	TF	0	294	0.6	1141499	9
	Composting	0	0	0.4	1541	0
	Total	340	642	2	2616361	20
5	CAS+N/P removal	340	230	2.7	2671669	20
	Composting	0	0	0.4	1606	0
	Total	340	230	3	2673275	20

Concepts	Technologies	OPEX		
		Sewerage system[1] (EUR/cap.year)	Treatment systems[2] (EUR/cap.year)	Total OPEX (EUR/cap.year)
1	ST	1	3	4
	TF	0	14	14
	CW	0	1	1
	Composting	0	0.02	0
	Total	1	18	19
2	UASB-ST	1	3	4
	TF	0	14	14
	CW	0	1	1
	Composting	0	0.02	0
	Total	1	19	20
3	UASB	1	2	3
	TF	0	14	14
	CW	0	1	1
	Composting	0	0.02	0
	Total	1	17	18
4	UASB	5	2	7
	TF	0	3	3
	Composting	0	0.02	0
	Total	5	5	11
5	CAS+N/P removal	3	16	19
	Composting	0	0.02	0
	Total	3	16	19

[1] The CAPEX and OPEX of sewerage systems (Euro/cap) was calculated based on the methodology described in section 2 of the supplementary materials

[2] The CAPEX and OPEX of treatment systems (Euro/cap) was calculated based on the methodology described in section 5 of the supplementary materials

[3] The CAPEX of land use costs (Euro/cap) was calculated based on typical land use costs (Euro/m^2) and total area (m^2) required of each technology per concept

Table S2.17 The land area requirement (m^2 and m^2/cap) per treatment technology in each sanitation concept.

Sanitation concepts	Technologies	Volume per unit[1] (m3)	Height of reactor[2] (m)	Area (m2)	Area (m2/cap)
Concept 1	ST	2.30	2.10	1.10	0.55
	TF	2.35	2.10	1.12	0.00
	CW	1.94	1.00	1.94	0.97
	Composting	7.54	1.00	7.54	0.01
Concept 2	UASB-ST	2.30	3.00	0.77	0.38
	TF	4.36	2.10	2.07	0.003
	CW	0.00	0.00	1.94	0.97
	Composting	8.25	1.00	8.25	0.01
Concept 3	UASB	28.62	3.00	9.54	0.01
	TF	7.37	2.10	3.51	0.005
	CW	1.94	1.00	1.94	0.97
	Composting	9.45	1.00	9.45	0.01
Concept 4	UASB	238.58	3.00	79.53	0.02
	TF	86.38	2.10	41.13	0.01
	Composting	59.28	2.00	29.64	0.01
Concept 5	CAS+N/P removal	1008.02	5.00	201.60	0.05
	Composting	61.77	2.00	30.88	0.01

[1]The volume of each technology per concept was calculated based on the methodology in the section 2 of the supplementary materials
[2]The height of technology was estimated based on literature values; ST (Philippi et al., 1999), UASB and UASB-ST (Metcalf et al., 2003), CAS (Tervahauta et al., 2013), and Composting (Wei et al., 2001)

S3. Supplementary Material Chapter 4

S3.1 List of stakeholders interviewed and participants of FGD on St. Eustatius

Table S3.1 List of local interviewees on St. Eustatius

	Interviewees	**Institution**
1	Department of Economic Affairs and Infrastructure	Government of St. Eustatius
2	Department of Agriculture (LVV)	Government of St. Eustatius
3	Department of Public Health	Government of St. Eustatius
4	Caribbean Netherlands Science Institute (CNSI)	Research Institute
5	St. Eustatius National Parks (STENAPA)	NGO
6	St. Eustatius Tourism Development Foundation	NGO

Table S3.2 List of participants of the FGD

No	Affiliation	Country
1	University of Puerto Rico	Puerto Rico
2	Department of Natural and Environmental Resources	Puerto Rico
3	Government of the Republic of Trinidad and Tobago Ministry of Local Government	Tobago
4	UNEP Haiti – Country Program Coordinator	Haiti
5	Ministry of Tourism, Culture & Information	Nevis
6	Department of Spatial Planning, Bonaire	Bonaire
7	Environmental Research Institute Charlotteville, Tobago	Tobago
8	Development Control Authority	Antigua
9	Sustainable Grenadines Inc	Saint Vincent and the Grenadines
10	Grenada Fisheries Division	Grenada
11	Government	St Lucia
12	Department of Fisheries	St Lucia
13	The Nature Conservancy	Haiti
14	Caribsave	Jamaica
15	Tunich-nah Consultants & Engineering	Belize
16	University of the West Indies	Jamaica

S3.2 Results of normalization

Resulting total scores per scenario (min-max normalization, 1-3 scale)

Unweighted total scores (Reference Situation)

Category	**Indicators**	Concepts				
		1	2	3	4	5
Environmental	1. Net energy use	0.507	1.000	0.930	0.928	0.000
	2a. Total N recovery	0.938	0.938	0.938	1.000	0.000
	2b. Total P recovery	0.000	0.000	0.000	1.000	1.000
	3. COD in the effluent	0.402	0.671	0.195	0.000	1.000
	4. Pathogen	0.000	1.000	1.000	1.000	1.000
	5. GHG emission	0.993	0.934	1.000	0.692	0.000
	6. Land use	0.000	0.107	0.356	1.000	0.987
Economic	7. CAPEX	0.101	0.000	0.061	1.000	0.949
	8. OPEX	0.022	0.000	0.154	1.000	0.066
Social-Cultural	9. Acceptance	0.214	0.000	0.286	0.500	1.000
	10. Competences and education required	1.000	0.857	0.762	0.238	0.000
Technological	11. Flexibility/adaptability	1.000	0.846	0.615	0.231	0.000
	12. Reliability/continuity of service	0.857	1.000	0.857	0.286	0.000
	Total	6.035	7.353	7.153	8.875	6.002
	Rank	4	2	3	1	5

Scenario 1

Category	Indicators	Concepts				
		1	2	3	4	5
Environmental	1. Net energy use	1.015	2.000	1.860	1.857	0.000
	2a. Total N recovery	1.875	1.875	1.875	2.000	0.000
	2b. Total P recovery	0.000	0.000	0.000	2.000	2.000
	3. COD in the effluent	0.805	1.341	0.390	0.000	2.000
	4. Pathogen	0.000	2.000	2.000	2.000	2.000
	5. GHG emission	1.986	1.869	2.000	1.384	0.000
	6. Land use	0.000	0.322	1.067	3.000	2.960
Economic	7. CAPEX	0.202	0.000	0.121	2.000	1.899
	8. OPEX	0.022	0.000	0.154	1.000	0.066
Social-Cultural	9. Acceptance	0.214	0.000	0.286	0.500	1.000
	10. Competences and education required	1.000	0.857	0.762	0.238	0.000
Technological	11. Flexibility/adaptability	1.000	0.846	0.615	0.231	0.000
	12. Reliability/continuity of service	2.571	3.000	2.571	0.857	0.000
	Total	10.690	14.110	13.702	17.067	11.925
	Rank	5	2	3	1	4

Scenario 2

Category	Indicators	Concepts				
		1	2	3	4	5
Environmental	1. Net energy use	1.522	3.000	2.790	2.785	0.000
	2a. Total N recovery	2.813	2.813	2.813	3.000	0.000
	2b. Total P recovery	0.000	0.000	0.000	3.000	3.000
	3. COD in the effluent	1.207	2.012	0.585	0.000	3.000
	4. Pathogen	0.000	3.000	3.000	3.000	3.000
	5. GHG emission	2.979	2.803	3.000	2.076	0.000
	6. Land use	0.000	0.107	0.356	1.000	0.987
Economic	7. CAPEX	0.303	0.000	0.182	3.000	2.848
	8. OPEX	0.022	0.000	0.154	1.000	0.066
Social-Cultural	9. Acceptance	0.214	0.000	0.286	0.500	1.000
	10. Competences and education required	1.000	0.857	0.762	0.238	0.000
Technological	11. Flexibility/adaptability	1.000	0.846	0.615	0.231	0.000
	12. Reliability/continuity of service	0.857	1.000	0.857	0.286	0.000
	Total	11.917	16.438	15.400	20.116	13.901
	Rank	5	2	3	1	4

Scenario 3

Category	Indicators	Concepts				
		1	2	3	4	5
Environmental	1. Net energy use	0.507	1.000	0.930	0.928	0.000
	2a. Total N recovery	0.938	0.938	0.938	1.000	0.000
	2b. Total P recovery	0.000	0.000	0.000	1.000	1.000
	3. COD in the effluent	0.402	0.671	0.195	0.000	1.000
	4. Pathogen	0.000	1.000	1.000	1.000	1.000
	5. GHG emission	0.993	0.934	1.000	0.692	0.000
	6. Land use	0.000	0.322	1.067	3.000	2.960
Economic	7. CAPEX	0.101	0.000	0.061	1.000	0.949
	8. OPEX	0.066	0.000	0.462	3.000	0.198
Social-Cultural	9. Acceptance	0.643	0.000	0.857	1.500	3.000
	10. Competences and education required	3.000	2.571	2.286	0.714	0.000
Technological	11. Flexibility/adaptability	3.000	2.538	1.846	0.692	0.000
	12. Reliability/continuity of service	2.571	3.000	2.571	0.857	0.000
	Total	12.222	12.975	13.212	15.384	10.107
	Rank	4	3	2	1	5

Scenario 4

Category	**Indicators**	Concepts				
		1	2	3	4	5
Environmental	1. Net energy use	1.015	2.000	1.860	1.857	0.000
	2a. Total N recovery	1.875	1.875	1.875	2.000	0.000
	2b. Total P recovery	0.000	0.000	0.000	2.000	2.000
	3. COD in the effluent	0.805	1.341	0.390	0.000	2.000
	4. Pathogen	0.000	2.000	2.000	2.000	2.000
	5. GHG emission	1.986	1.869	2.000	1.384	0.000
	6. Land use	0.000	0.107	0.356	1.000	0.987
Economic	7. CAPEX	0.202	0.000	0.121	2.000	1.899
	8. OPEX	0.066	0.000	0.462	3.000	0.198
Social-Cultural	9. Acceptance	0.643	0.000	0.857	1.500	3.000
	10. Competences and education required	2.000	1.714	1.524	0.476	0.000
Technological	11. Flexibility/adaptability	2.000	1.692	1.231	0.462	0.000
	12. Reliability/continuity of service	0.857	1.000	0.857	0.286	0.000
	Total	11.449	13.599	13.533	17.965	12.083
	Rank	5	2	3	1	4

Table S4.3 Results of Z-score for each sanitation concept per scenario

Baseline Conditions

Conditions	Baseline Conditions				
Indicators	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Environmental	-0.474	0.133	0.023	0.461	-0.143
Rank Environmental	5	2	3	1	4
Economic	-0.653	-0.794	-0.524	1.629	0.342
Rank Economic	4	5	3	1	2
Social Cultural	0.284	-0.217	0.080	-0.286	0.140
Rank Cultural	1	4	3	5	2
Technological	0.949	0.928	0.435	-0.817	-1.495
Rank Technological	1	2	3	4	5
Overall indicators	0.027	0.013	0.003	0.247	-0.289
Rank Overall Indicators	2	3	4	1	5

Scenario 1

Conditions	Scenario 1				
Indicators	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Environmental	-1.422	0.399	0.068	1.383	-0.429
Rank Environmental	5	2	3	1	4
Economic	-0.653	-0.794	-0.524	1.629	0.342
Rank Economic	4	5	3	1	2
Social Cultural	-0.262	-1.394	-0.257	0.008	1.905
Rank Cultural	4	5	3	2	1
Technological	1.899	1.855	0.869	-1.634	-2.989
Rank Technological	1	2	3	4	5
Overall indicators	-0.110	0.017	0.039	0.346	-0.293
Rank Overall Indicators	4	3	2	1	5

Scenario 2

Conditions	Scenario 2				
Indicators	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Environmental	-1.688	0.230	-0.100	1.465	0.094
Rank Environmental	5	2	4	1	3
Economic	-0.653	-0.794	-0.524	1.629	0.342
Rank Economic	4	5	3	1	2
Social Cultural	-0.262	-1.394	-0.257	0.008	1.905
Rank Cultural	4	5	3	2	1
Technological	1.899	1.855	0.869	-1.634	-2.989
Rank Technological	1	2	3	4	5
Overall indicators	-0.176	-0.025	-0.003	0.367	-0.162
Rank Overall Indicators	5	3	2	1	4

Scenario 3

Conditions	Scenario 3				
Indicators	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Environmental	-0.787	0.496	0.192	1.154	-1.054
Rank Environmental	4	2	3	1	5
Economic	-1.959	-2.381	-1.572	4.886	1.027
Rank Economic	4	5	3	1	2
Social Cultural	1.399	0.526	0.575	-1.153	-1.347
Rank Cultural	1	3	2	4	5
Technological	0.949	0.928	0.435	-0.817	-1.495
Rank Technological	1	2	3	4	5
Overall indicators	-0.100	-0.108	-0.093	1.017	-0.717
Rank Overall Indicators	3	4	2	1	5

Scenario 4

Conditions	Scenario 4				
Indicators	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Environmental	-1.054	0.327	0.023	1.236	-0.531
Rank Environmental	5	2	3	1	4
Economic	-1.959	-2.381	-1.572	4.886	1.027
Rank Economic	4	5	3	1	2
Social Cultural	1.399	0.526	0.575	-1.153	-1.347
Rank Cultural	1	3	2	4	5
Technological	0.949	0.928	0.435	-0.817	-1.495
Rank Technological	1	2	3	4	5
Overall indicators	-0.166	-0.150	-0.135	1.038	-0.586
Rank Overall Indicators	4	3	2	1	5

Average Conditions

Conditions	Scenario 4				
Indicators	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Environmental	-1.085	0,317	0.041	1.140	-0.413
Rank Environmental	5	.2	3	1	4
Economic	-1.176	-1.429	-0.943	2.932	0.616
Rank Economic	4	5	3	1	2
Social Cultural	0.511	-0.390	0.143	-0.515	0.251
Rank Cultural	1	4	3	5	2
Technological	1.329	1.299	0.609	-1.144	-2.092
Rank Technological	1	2	3	4	5
Overall indicators	-0.105	-0.051	-0.038	0.603	-0.409
Rank Overall Indicators	4	3	2	1	5

S4. Supplementary Material Chapter 5

Table S4.1 List of quantification methods per flow and the assumptions

Flow	Description	Quantification method	Assumptions[1] and references
F1	Crop uptake	F1=F2+F3	Calculated from the mass balance of "Crop production" sub-system
F2	Vegetable products	F28*Nutrient Use Efficiency (NUE) of treated effluent + F18*NUE of compost	NUE – Nitrogen of treated effluent (40%), compost (16%). NUE – Phosphorus of treated effluent (90%), Compost (90%). It is assumed that available nutrients from treated effluent and compost fertilizer will be distributed equally to seven different local crops on St. Eustatius which determining nutrients absorbed/uptake by Crops.
F3 F4	Feed	Total feed: (Live animals * Nutrient (N,P) requirement per animal (kg/year)*correction factor)+ (Live animals for slaughter*Live weight (kg per head)*N,P contents per kg animals weight)	Number of live animals (Debrot et al., 2015); Nutrient (N,P) requirement per animal for maintenance of beef cattle (67.5 gN/day, 13 gP/day) (NRC, 2000), goat (5.3 gN/day, 1 gP/day) (NRC, 2007), and sheep (6.4 gN/day, 1.3 gP/day) (NRC, 2007); correction factor of beef cattle (0.6), goats (1), and sheep (0.8)

		Imported feed (F4): Fenced animals * Ratio of imported feed consumed by fenced animals Local feed (F3): Total feed – F4	(FAO, 2015); Live animals for slaughter (LVV, 2014); Live weight based on Tropical Livestock Unit (TLU) of beef cattle (250 kg), goats (30 kg), and sheep (30 kg) (FAO, 2015); N and P content per kg animal live weight of beef cattle (27 gN/kg, 7.4 gP/kg), goat (24 gN/kg,7.9 gP/kg), and sheep (25g N/kg,7.8 gP/kg) (Bruggen, 2007); Number of fenced animals (20% of live animals); Ratio of imported feed consumed by fenced animals (50%)
F5	Livestock for slaughter	Live animals for slaughter* Live weight (kg per head)*N,P contents per kg animal live weight	Number of live animals for slaughter (LVV, 2014); Live weight based on Tropical Livestock Unit (TLU) of beef cattle (250 kg), goats (30 kg), and sheep (30 kg) (FAO, 2015); N and P content per kg animal live weight of beef cattle (27gN/kg, 7.4gP/kg), goat (24gN/kg,7.9 gP/kg), and sheep (25 gN/kg,7.8 gP/kg) (Bruggen, 2007)
F6	Exported animal product	Live animals for slaughter (export only)* Live weight (kg per head)*N,P contents per kg animal live weight -	Number of live animals for slaughter (export)= exported animal products (carcasses)/fraction animal to carcass (LVV, 2014);

		Slaughter waste of exported products (kg)* N,P contents	fraction animal to carcass of beef cattle (0.635), goats and sheep (0.5) (Smit, 2014); N and P content per kg animal live weight of beef cattle (27 gN/kg, 7.4 gP/kg), goat (24 gN/kg,7.9 gP/kg), and sheep (25 gN/kg,7.8 gP/kg) (Bruggen, 2007); Slaughter waste of exported products=total live weight-carcass weight; N and P content per kg slaughter waste is assumed equal to the meat of beef cattle (22.2 gN/kg, 2 gP/kg), goats and sheep (20.6 gN/kg, 1.8 gP/kg) (Foodsel, 2008)
F7	Slaughtered animal waste	Slaughter waste from exported products (kg)* N,P contents + Live animals for slaughter (local only)* Live weight (kg per head)*N,P contents - Meat products (kg)*N,P contents	Slaughter waste of exported products=total live weight-carcass weight; N and P content per kg slaughter waste is assumed equal to the meat of beef cattle (22.2 gN/kg, 2 gP/kg), goats and sheep (20.6 gN/kg, 1.8 gP/kg) (Foodsel, 2008); Number of live animals for slaughter (monthly local consumption: beef cattle (4), goats (20), sheep (10) (LVV, 2014); Live weight based on Tropical Livestock Unit (TLU) of beef cattle (250 kg), goats

			(30 kg), and sheep (30 kg) (FAO, 2015); Meat products=Total live weight*Fraction meat from total weight of beef cattle (0.381), goats and sheep (0.3) (Smit, 2014); N and P content per kg meat of beef cattle (22.2 gN/kg, 2 gP/kg), goats and sheep (20.6 gN/kg, 1.8 gP/kg) (Foodsel, 2008)
F8	Biological nitrogen fixation	Type of land (ha)*N fixation factor (kg/ha)	Total agricultural land required=170 ha (3.6 ha of existing agricultural land+50% of existing pastures (70.1 ha)+ remaining shrub and bush rangeland (68.3 ha). Thus, the remaining land after conversion: Total pastures (70 ha), shrub and bush rangeland (699.7 ha), forest (866 ha), Bare/sparsely vegetated (151 ha) (Smith et al., 2013); N fixation factor for grassland (2.7 kgN/ha), forest and shrubland (23 kgN/ha) (Cleveland et al., 1999)
F9	Manure	F9=F3+F4-F5	Calculated from the mass balance of "Animal production" sub-system

F10	Food	Total food protein intake (g/cap per day)*N,P contents	N=0.13*Total food protein (gN/cap per day); P =0.011* (Total food protein+plant food protein) (gP/cap per day) (Vinnerås and Jönsson, 2002); Total food protein intake for Netherland Antilles is 93.2 g/cap per day (FAOSTAT, 2014);
F11	Market waste	Market waste production*Dry matter content*N,P content	Market waste 193 ton/year (DEI, 2014); Dry matter content (40%) (Eggleston et al., 2006), N content 3.16%, and P content (0.52%) (Zhang et al., 2007)
F12	Imported food	F12=F2+F5+F14-F7-F10-F11-F13	Calculated from the mass balance of "Market" sub-system
F13	Detergent use	F13=0	For P it is assumed that Phosphate Free Detergent will be applied.
F14	Imported detergent	F14=0	It is assumed that the total detergent used is imported
F15	Mixed blackwater and greywater	F15=F10+F13-F15-F16	Calculated from the mass balance of "Household Consumption" sub-system
F16	Kitchen waste	Kitchen waste production*Dry matter content*N,P content	Kitchen waste is 387 ton/year (DEI, 2014); Dry matter content (40%)

			(Eggleston et al., 2006), N content (3.16%), and P content (0.52%) (Zhang et al., 2007)
F17	Imported fertilizer	assumed to be "0" as recovered nutrients from domestic waste and wastewater will be reused in agriculture	
F18	Treated effluentTreated effluent	F18=(F15)* (1-Nutrient Removal efficiencies)	Nutrient removal efficiencies of UASB-TF: N (27%), and for P (5%) Firmansyah et al. (2021)
F19	N-gas emission of UASB+TF	F19=(F15)*N gas emission factor	0.016 (Firmansyah et al., 2021)
F20	Sludge	For N, F20=F15-F18-F19 For P, F20= F15-F18	
F21	N-gas emission of landfill	Total N input to landfill*Transfer coefficient of N-gas emission of landfill	Transfer coefficient of N-gas emission (16–25%) (Onay and Pohland, 1998)
F22	Leaching/Run-off of N	F22=(F8+F9+F17+F23-F1)*60% (Sutton, 2013)	Of the surplus, N is lost through ammonia emission (24%), soil denitrification (16%), and N leaching and runoff (60%) (Sutton, 2013)

	Erosion/run-off of P	Total land (ha)*average rate of P erosion in three Caribbean islands (kgP/ha per year)*ratio rainfall at St. Eustatius with the islands	Total land (2109 ha) (Smith et al., 2013); average rate of P erosion in Dominica, St Lucia, and St. Vincent (0.134 kgP/ha per year), ratio rainfall is half of the islands.
F23	Atmospheric deposition	Total land area (ha)*Atmospheric deposition factor (kg/ha)	Total land area: 2109 ha (Smith et al., 2013); N deposition (0.5 – 1 kgN/ha per year)(Galloway et al., 2004); P deposition (0.63 kgP/ha per year) (Tipping et al., 2014)
F24	N-gas emission of fertilizer and manure	F24=(F8+F9+F17+F23-F1)*40% (Sutton, 2013)	Of the surplus, N is lost through ammonia emission (24%), soil denitrification (16%), and N leaching and runoff (60%) (Sutton, 2013)
F25	Compost	For N, F25=(F11+F16+F20)-(F26+F27) For P, F25=F11+F16+F20	Calculated from the mass balance of "composting" sub-system
F26	N-gas emission of composting	F26=(F11+F16)*23.2% + F20*27.2%	Based on the data N-losses from food waste and sewage sludge (Pardo et al., 2015)
F27	Leachate composting	F27=(F11+F16)*22.2% + F20*15.5%	Based on the data on N-losses from food waste and

			sewage sludge (Pardo et al., 2015)
F28	Leachate landfill	F28=F7*Transfer coefficient of N in leachate	Transfer coefficient of N in leachate (21-27%) (Wang et al., 2014), No P leaching is assumed
F29	Leaching	F29=F27+F28	Calculated from the mass balance of "non-agricultural lands" sub-system

[1] Where a range is given, the average value is used in the calculations

Table S4.2 Crops yield, cultivation areas, and average TN and TP

Crops[1]	**Cultivation area (ha)[1]**	**Yield (kg/year)[1]**	**Yield (kg/ha/y)**	**Average TN (g/100 g edible porsion)[2]**	**KgN/y**	**Average TP (mg/100 g edible porsion)[2]**	**KgP/y**	**Ratio TN/TP**
Tomatoes	0.61	8575	14,126.20	0.15	12.86	22	1.89	6.82
Cucumber	0.20	9485	46,875.85	0.1	9.49	15	1.42	6.67
Lettuce	0.05	3655	72,253.61	0.2	7.31	23	0.84	8.70
Water Melon	0.10	3675	36,324.49	0.1	3.68	9	0.33	11.11
Spinach	0.05	816.47	16,140.26	0.42	3.43	46	0.38	9.13
Pineapple	0.10	1600	15,814.75	0.07	1.12	9	0.14	7.78
Pumpkins	0.10	4605	45,516.82	0.18	8.29	44	2.03	4.09
Average crop	**1.21**		**26,696.83**	**0.14**	**46.17**	**21.68**	**7.03**	**6.57[3]**

[1](Hazel, 2014)
[2](Souchi, 2001)
[3]Calculated based on the ratio of Average TP and Average TN of all crops

Table S4.3 Coefficient variance (CV) that is used in STAN 2.5 for data uncertainty

Flow	Description	Mass flow & N and P content			
		Mass flow	CV mass flow	N and P content	CV N and P content
F1	Crop uptake	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN
F2	Vegetable products	Tomatoes (7650 kg/year), Cucumber (8765 kg/year), Lettuce (3265 kg/year), Water melon (3360 kg/year), Spinach (406 kg/year), Pineapple (1600 kg/year), Pumpkin (4425 kg/year) (Hazel, 2014	50%	Tomatoes (1.5 gN/kg, 0.22 gP/kg), cucumber (1 gN/kg, 0.15 gP/kg), lettuce (2 gN/kg, 0.23 gP/kg), water melon (1 gN/kg, 0.09 gP/kg), spinach (4.2 gN/kg, 0.46 gP/kg), pineapple (0.7 gN/kg, 0.09 gP/kg), pumpkins (1.8 gN/kg, 0.44 gP/kg) (Souchi, 2001)	25 %
F3	Local Feed	Cows (1012), goats (2470), sheep (1300) (Debrot et al., 2015)	10%	Nutrient (N,P) requirement per animal for maintenance of beef cattle (67.5 gN/day, 13 gP/day) (NRC, 2000), goat (5.3 gN/day, 1 gP/day) (NRC, 2007), and sheep (6.4 gN/day, 1.3 gP/day) (NRC, 2007)	10%

Flow	Description	Mass flow & N and P content			
		Mass flow	CV mass flow	N and P content	CV N and P content
F4	Imported feed	Cows (1012), goats (2470), sheep (1300) (Debrot et al., 2015)	10%	Nutrient (N,P) requirement per animal for maintenance of beef cattle (67.5 gN/day, 13 gP/day) (NRC, 2000), goat (5.3 gN/day, 1 gP/day) (NRC, 2007), and sheep (6.4 gN/day, 1.3 gP/day) (NRC, 2007)	10%
F5	Livestock for slaughter	Beef cattle (4 per month), goats (20 per month) and sheep (10 per month) (LVV, 2014) Live weight based on Tropical Livestock Unit (TLU) of beef cattle (250 kg), goats (30 kg), and sheep (30 kg) (FAO, 2015)	25%	Beef cattle (27gN/kg, 7.4gP/kg), goat (24gN/kg,7.9 gP/kg), and sheep (25 gN/kg,7.8 gP/kg) (Bruggen, 2007)	10%
F6	Exported animal product	Carcass meat of beef cattle (18583 kg/year), Goat (328 kg/year), Sheep (1126 kg/year) (LVV, 2014)	25%	Beef cattle (27 gN/kg, 7.4 gP/kg), goat (24 gN/kg,7.9 gP/kg), and sheep (25 gN/kg,7.8 gP/kg) (Bruggen, 2007)	10%

Flow	Description	Mass flow & N and P content			
		Mass flow	**CV mass flow**	**N and P content**	**CV N and P content**
F7	Slaughtered animal waste	Beef cattle (4 per month), goats (20 per month) and sheep (10 per month) (LVV, 2014), Live weight based on Tropical Livestock Unit (TLU) of beef cattle (250 kg), goats (30 kg), and sheep (30 kg) (FAO, 2015)	25%	beef cattle (22.2 gN/kg, 2 gP/kg), goats and sheep (20.6 gN/kg, 1.8 gP/kg) (Foodsel, 2008)	25%
F8	Biological nitrogen fixation	Pastures (70 ha), Rangeland (699.7 ha), Forest(866 ha), Bare/sparsely vegetated (151 ha) (Smith et al., 2013)	10%	N fixation factor for grassland (2.7 kgN/ha), forest and shrubland (23 kgN/ha) (Cleveland et al., 1999)	10%
F9	Manure	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN
F10	Food	Total food protein supply for Netherland Antilles is 93.2 g/cap per day, total vegetable/plant protein 34.7 g/cap per day (FAOSTAT, 2014)	10%	N=0.13*Total food protein (gN/cap per day); (Vinnerås and Jönsson, 2002)	10%

Flow	Description	Mass flow & N and P content			
		Mass flow	**CV mass flow**	**N and P content**	**CV N and P content**
F11	Market waste	Market waste (35.4 kg/cap per year) (DEI, 2014)	10%	Dry matter content (40%) (Eggleston et al., 2006), N (3.16%), and P (0.52%) (Zhang et al., 2007)	25%
F12	Imported food	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN
F13	Detergent use	-	-	-	-
F14	Imported detergent	-	-	-	-
F15	Mixed Blackwater and Greywater	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN
F16	Kitchen waste	Kitchen waste (39.3 kg/cap per year) (DEI, 2014)	10%	Dry matter content (40%) (Eggleston et al., 2006), N content (3.16%), and P content (0.52%) (Zhang et al., 2007)	25%
F17	Imported fertilizer	-	-	-	-

Flow	Description	Mass flow & N and P content			
		Mass flow	CV mass flow	N and P content	CV N and P content
F18	Treated effluent	-	-	Nutrient removal efficiencies of UASB-TF: N (27%), and for P (5%) Firmansyah et al. (2021)	10%
F19	N-gas emission of UASB+TF	-	-	0.016 (Firmansyah et al., 2021)	25%
F20	Sludge	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN
F21	N-gas emission of landfill	-	-	Transfer coefficient of N-gas emission (20.5%) (Onay and Pohland, 1998)	25%
F22	Leaching/Run-off of N	-	-	Of the surplus, N is lost through ammonia emission (24%), soil denitrification (16%) (Sutton, 2013)	25%
	Erosion/run-off of P	Total land area: 2109 ha (Smith et al., 2013)	10%	Average rate of P erosion in Dominica, St Lucia, and St. Vincent (0.134 kgP/ha per year) (McDowell, 1995), Ratio rainfall at St. Eustatius is half of the other islands.	25%

Flow	Description	Mass flow & N and P content			
		Mass flow	CV mass flow	N and P content	CV N and P content
F23	Atmospheric deposition	Total land area: 2109 ha (Smith et al., 2013)	10%	N deposition (0.75 kgN/ha per year)(Galloway et al., 2004); P deposition (0.05 kgP/ha per year) (Tipping et al., 2014)	25%
F24	N-gas emission of fertilizer and manure	-	-	Of the surplus, N is lost through ammonia emission (24%), soil denitrification (16%) (Sutton, 2013)	25%
F25	Compost	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN
F26	N-gas emission of composting	-	-	Based on the data N-losses from food waste and sewage sludge (Pardo et al., 2015)	25%
F27	Leachate composting	-	-	Based on the data on N-losses from food waste and sewage sludge (Pardo et al., 2015)	25%
F28	Leachate landfill	-	-	Transfer coefficient of N in leachate (21-27%) (Wang et al., 2014), No P leaching is assumed.	25%
F29	Leaching	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN

Table S4.3 N and P flows in St. Eustatius with insert and reconciled value in STAN 2.5 for a new sanitation system applied

Flow	Description	Insert value to STAN				Reconciled value in STAN			
		N flow (kgN/year)	**N flow Uncertainty (%)**	**P flow (kgP/year)**	**P flow uncertainty (%)**	**N flow (kgN/year)**	**N Uncertainty (%)**	**P flow (kgP/year)**	**P uncertainty (%)**
F1	Crop uptake	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN	21,123	13	4217	14
F2	Vegetable products	5403	54	822	54	5403	54	822	54
F3	Local Feed	21,077	13	4,210	14	21,077	13	4,210	14
F4	Imported feed	2,181	13	422	14	2,181	13	422	14
F5	Livestock for slaughter	1,449	26	413	26	1,449	26	413	26
F6	Exported animal product	595	29	215	28	595	29	215	28
F7	Slaughtered animal waste	685	34	183	35	685	34	183	35

Flow	Description	Insert value to STAN				Reconciled value in STAN			
		N flow (kgN/year)	N flow Uncertainty (%)	P flow (kgP/year)	P flow uncertainty (%)	N flow (kgN/year)	N Uncertainty (%)	P flow (kgP/year)	P uncertainty (%)
F8	Biological nitrogen fixation	39673	14	0	0	41,430	12	0	0
F9	Manure	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN	21,809	13	4,219	14
F10	Food	18,101	14	2,102	14	18,101	14	2,102	14
F11	Market waste	1,826	27	301	27	1,826	27	301	27
F12	Imported food	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN	14,355	27	1,566	36
F13	Detergent use	0	0	0	0	0	0	0	0
F14	Imported detergent	0	0	0	0	0	0	0	0
F15	Mixed Blackwater and Greywater	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN	16,068	16	1,767	17

Flow	Description	Insert value to STAN				Reconciled value in STAN			
		N flow (kgN/year)	**N flow Uncertainty (%)**	**P flow (kgP/year)**	**P flow uncertainty (%)**	**N flow (kgN/year)**	**N Uncertainty (%)**	**P flow (kgP/year)**	**P uncertainty (%)**
F16	Kitchen waste	2,033	27	335	27	2,033	27	335	27
F17	Imported fertilizer	0	0	0	0	0	0	0	0
F18	Treated effluent	11,729	10	1,679	10	11,729	10	1,679	18
F19	N-gas emission of UASB+TF	257	25	0	0	257	25	0	0
F20	Sludge	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN	4,082	10	88	10
F21	N-gas emission of landfill	137	29	0	0	137	29	0	0
F22	Leaching/Run-off of N	Calculated in STAN	Calculated in STAN	0	0	390	50	0	0
	Erosion/run-off of P	0	0	141	27	0	0	141	27

Flow	Description	Insert value to STAN				Reconciled value in STAN			
		N flow (kgN/year)	**N flow Uncertainty (%)**	**P flow (kgP/year)**	**P flow uncertainty (%)**	**N flow (kgN/year)**	**N Uncertainty (%)**	**P flow (kgP/year)**	**P uncertainty (%)**
F23	Atmospheric deposition	1,591	27	105	25	1,591	27	105	25
F24	N-gas emission of fertilizer and manure	21,108	16	0	0	21,108	16	0	0
F25	Compost	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN	4,446	64	724	17
F26	N-gas emission of composting	2,006	25	0	0	2,006	25	0	0
F27	Leachate composting	1,489	25	0	0	1,489	25	0	0
F28	Leachate landfill	171	25	0	0	171	25	0	0
F29	Leaching	Calculated in STAN	Calculated in STAN	Calculated in STAN	Calculated in STAN	1660	23	0	0

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Summary

The development of sanitary systems is of the utmost importance because large numbers of households do not have access to an improved sanitary system, leading to environmental, social and public health problems. Moreover, produced domestic waste and wastewater contains resources, such as nutrient, water, organic matter that can be reused in agriculture. Nutrients contained in recovery products, such as nitrogen (N) and phosphorus (P), are essential macronutrients for crop production that can contribute to low use of fossil energy and replenish the P reserves. This can contribute to a circular economy and finally replace the linear metabolism of cities or urban areas or islands. Several sanitation planning approaches have been developed aiming to solve the aforementioned problems. However, these approaches do not consider the full train of sanitation technologies (collection, transport, treatment/recovery) and are lacking an integration between sanitation and agricultural systems. The existing approaches are also not considering the four domains of sustainability, viz. environmental, technological, social-cultural, and economic, and the impact of future development trends on the performance of sanitation technology.

The main objective of this thesis was to develop a new planning approach to support recovery and reuse of nutrients, coupling sanitation and agricultural systems, while accounting for different future development scenarios. Hence, the sub-objectives of the research were:

1. To develop a framework that facilitates a structured analysis of the link between sanitation and agricultural systems with regards to nutrient supply and demand
2. To identify strategies for implementation of sanitation concepts in urban areas to recover nutrients from domestic waste(water) and reuse in agriculture
3. To assess the effect of different future development scenarios on the performance and selection of sanitation concepts
4. To assess the impact of agricultural reuse of nutrients for optimising nutrients recovery from domestic waste(water)

St. Eustatius, a small island in the Dutch Caribbean, was selected as a case study to develop the approach. The study at island-level offers opportunities for analyzing the interactions between urban (residential areas) and rural (agricultural activities) sectors in a terrestrial region. It is a relevant scale for identifying the key forces underlying nutrient use at present and opportunities for better nutrient resource

management in the future. An island as case study also provided a clearly delineated area to assess the link between sanitation and agriculture focusing on nutrient recovery and reuse. Moreover, most small tropical islands are remote and therefore self-sufficiency of food production is an important theme for sustainable development.

The thesis breaks down into four main chapters, introduction and a discussion chapter.

Chapter 2 provides an overview of the baseline conditions of nutrient (N and P) management of a small island considering the limited data availability on the island. A substance Flow Analysis (SFA) model is developed to identify intervention points that can provide N and P stocks for agricultural production considering the existing sanitation and agricultural systems. The model consists of eight sub-systems, viz. agricultural and natural lands, urban lands, crop production, animal production, market, household consumption, soakage pit and open-dump landfill. A total of 26 flows were identified and quantified for a period of one year using data of 2013. The results show N and P loss from the island through erosion/run-off and leaching from agricultural systems. Moreover, unimproved sanitation systems contribute to the loss of N and P through leaching and atmospheric emission. The interventions or mitigation measures proposed in this study are treatment/recovery of domestic waste and wastewater streams for reuse in agriculture. Several potential sanitation systems, in connection with agricultural reuse of the products can be applied to improve nutrient management on the island.

In Chapter 3, different mitigation measures are compared for its potential nutrient recovery and reuse. The assessment is executed for a full train of technologies, consisting of collection, transport, treatment and reuse. Three decentral, source separation concepts and two centralized treatment concepts with mixed blackwater and greywater are compared and assessed for their performance for different sustainability indicators. Composting is applied for all concepts. The assessment includes 13 sustainability indicators representing four domains of sustainability indicators: environmental (net energy use, TN recovery, TP recovery, BOD/COD, pathogens, and GHG emission, land use), economic (CAPEX and OPEX), social cultural (acceptance, required competences and education), and technological (flexibility/adaptability, reliability/continuity of service) indicators. The best performing concept is the application of a conventional sewer, combining black and grey water, followed by an Upflow Anaerobic Sludge Bed (UASB) and Trickling Filter (TF) at island level for treatment/recovery with subsequent reuse in agriculture. UASB sludge is composted in combination with separately collected kitchen waste.

Chapter 4 extends the assessment of the selected sanitation concepts by determining the effect of different future development on the performance of sanitation concepts that will influence the selection of the sanitation concepts for application. Future development is analyzed through trend analysis and developing four external scenarios. The assessment involves identifying the relative importance (weights) of 13 sustainability indicators for different future scenarios. The results are combined using Multi Criteria Decision Making (MCDM) model. The sanitation concept with the overall best performance across different future scenarios is the Upflow Anaerobic Sludge Bed (UASB) and Trickling Filter (TF) at island level.

In chapter 5, the best performing concept, with respect to four domain of indicators under different future scenarios, is selected for further assessment with regards to the reuse effects in agricultural systems. The recovered products (treated effluent and compost) are assessed for its effect on nutrient flows on the island comparing the baseline condition with a system where recovered nutrients are used in agriculture on the island. A SFA model of a new system is developed to portray the changes in N and P flows. It is clear from the model that the reuse of total recovered nutrients from the sanitation systems can increase the local crop production, minimize the imported food, self-sufficiency of fertilizer, and reduce the nutrient losses on the island. To increase the local crop production, applying recovered nutrients, the area of arable land needs to increase from 3.6 ha to 142 ha at the expense of the area of pasture and shrub land. Compared to the baseline conditions, the reuse of recovered nutrients can reduce N losses by 4% and P remain constant. However, P is used for food production and some P accumulates in agricultural soil instead of in soakage pits or landfill.

The overall approach with its scientific and social contribution is presented and discussed in Chapter 6. This chapter also includes the limitations and potential extension for future research. The new planning approach follows the structure of this thesis. An understanding of the nutrient flows should first be developed, by

applying MFA or SFA approach. Secondly, the sanitation technological selection should be carried out in a holistic way considering different domains of sustainability. The third step involves developing different future scenarios and assessing how these affect the performance and selection of the sanitation concepts. The fourth and final step is an integrated assessment of sanitation and agriculture, assessing the effect of nutrient recovery and reuse in agriculture. The application of the approach can provide holistic information for decision makers and planners to plan more sustainable sanitation-agricultural systems, which will contribute to the achievement of several SDGs, especially SDG 6 related to clean water and sanitation.

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About the Author

Curriculum Vitae

Indra Firmansyah (or Indra) was born as the oldest of four in Merauke, Papua-Indonesia, on the 4th of April 1983. In 2006 he completed his bachelor study in Insitute Technology of Sepuluh Nopember, Surabaya, Indonesia. He got a scholarship to work on his BSc thesis in Kobe University, Japan where he focused on the reduction of particulate matter from diesel exhaust gas emission. Since then, he is interested in environmental problems and issues that need solutions to be properly managed. In 2009, he started his Master at Urban Environmental Management Program of Wageningen University with specialisation in Environmental Technology and Management. For his MSc study he got a scholarship from STUNED. He did his thesis in Environmental Technology Group (ETE). The thesis focussed on the possibilities to apply algae treatment technologies for domestic wastewater treatment. After graduated in 2011, he returned to Indonesia and continue working as a technical consultant in RoyalHaskoningDHV Indonesia that focused on the development of water and sanitation in different cities in Indonesia. In 2013, he got a PhD grant from Ministry of Economic Affairs of Kingdom of the Netherlands to pursue his study at ETE in collaboration with Land Use Planning (LUP) Group and Plant Research International (PRI) in Wageningen University, The Netherlands. The project is part of TripleP@Sea Project that focused on zero nutrient discharge and nutrient reuse in agriculture. In 2018, one of his published papers was selected as Top 3 awardee for Jaap van der Graaf award for its societal relevance, innovation, practicality, scientific content and language. Currently, he is an Executive Director of a Consultancy Company namely PT. Permata Putra Bengawan which provides consultancies related to sustainability issues such as Environmental and Impact Assessment (ESIA) and Social Return on Investment (SROI). He is also a resource person in the Faculty of Agro-Industrial Technology of Padjadjaran University, Indonesia that involved in several projects.

Overview of scientific publications

Peer reviewed scientific publications

Firmansyah, I., G. J. Carsjens, F. J. de Ruijter, G. Zeeman, and M. Spiller. 2021. An integrated assessment of environmental, economic, social and technological parameters of source separated and conventional sanitation concepts: A contribution to sustainability analysis. Journal of Environmental Management 295:113131.

Firmansyah, I., M. Spiller, F. J. de Ruijter, G. J. Carsjens, and G. Zeeman. 2017. Assessment of nitrogen and phosphorus flows in agricultural and urban systems in a small island under limited data availability. Science of The Total Environment 574:1521-1532.

Kerstens, S., G. Hutton, I. Firmansyah, I. Leusbrock, and G. Zeeman. 2016. An Integrated Approach to Evaluate Benefits and Costs of Wastewater and Solid Waste Management to Improve the Living Environment: The Citarum River in West Java, Indonesia. Journal of Environmental Protection 7(11):1439.

Firmansyah, I, M. Spiller, F.J. de Ruijter, G. Zeeman, and G.J. Carsjens. An approach to evaluate the performance of sanitation systems under different future developments: A case study in St. Eustatius. *To be submitted*

Firmansyah, I, M. Spiller, G.J. Carsjens, G. Zeeman, and F.J. de Ruijter. Effect of domestic waste and wastewater reuse in agriculture on nutrient flows of a small tropical island. *To be submitted*

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- SENSE writing (2016)
- Research in context activity: 'Initiating and organizing Focus Group of Discussion on Scenario Development of Small Islands in the Caribbean' (2016)

Other PhD and Advanced MSc Courses

- Workshop Material Flow Analyses with STAN 2.5, TU Vienna (2013)
- Scientific Publishing & Scientific Writing, Wageningen Graduate Schools (2013)
- Teaching and Supervision MSc Thesis, Wageningen Graduate Schools (2014)
- Review Scientific Paper, Wageningen Graduate Schools (2015)
- Pitch yourself, Wageningen Graduate Schools (2015)
- Technique for writing and presenting a scientific paper, Wageningen Graduate Schools (2015)
- Summer School: Small Island Natural Resource Development: Sustainable Coastal Management, UNESCO-IHE/CNSI (2015)
- Biogas Compact Course and Workshop, University of Oldenburg (2017)

Management and Didactic Skills Training

- Supervising three MSc thesis students (2013-2016)
- Supervising one BSc thesis student with internship (2016)

Oral Presentations

- *Recovered resources (water and nutrients) from domestic waste(water) in agriculture; Case Study: St. Eustatius*. The opening seminar of Research Centre of Caribbean, 24-25 April 2014, St. Eustatius, The Netherlands
- *Assessment of the impact of sanitation systems on closing N and P cycles in urban-agricultural systems*. The Environmental Technology for Impact Conference (ETEI2015), 29-30 April 2015, Wageningen, The Netherlands
- *Nutrient (N and P) flows in agricultural and sanitation systems: Case study of a small island*. Amsterdam Metabolism Workshop, 20 May 2015, Amsterdam, The Netherlands
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SENSE coordinator PhD education

Dr. ir. Peter Vermeulen

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