THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

A Journey towards Sustainable Small Wastewater Treatment Systems in Low and Lower–Middle Income Countries

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Cover: Illustration of the sustainability dimensions identified in the thesis.

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ABSTRACT

The sustainability of small wastewater treatment systems (WWTSs) in low and lower-middle income countries represents a challenge in terms of functionality and optimal performance in the ongoing effort to treat wastewater sufficiently to enable safe discharge or reuse. The reuse of wastewater is a common practice in these countries, especially where water resources are scarce. However, current practice does not always ensure that public health risks are avoided. The sustainable development goals (SDGs) include the target of halving the proportion of untreated wastewater by 2030 (SDG 6.3). To achieve this, it is crucial to identify and understand the challenge of having sustainable WWTSs that operate optimally, and to support the formulation of effective strategies for implementing more sustainable systems. In this thesis, a case study approach was used to investigate nine small WWTSs in Cochabamba, Bolivia. A WWTS consists of the collection system, i.e. the sewer network, and the wastewater treatment plant (WWTP). Quantitative data was collected in the field from the WWTPs and qualitative data was collected regarding the sewer network and the users. A body of knowledge was built up dealing with the specific difficulties experienced at these WWTSs in achieving optimal performance and how the actual performance impacts on human health and ecological risks in areas where wastewater irrigation is practised. This body of knowledge was used to acquire a greater understanding of how the sustainability of small WWTSs can be assessed. Systematization of standard sustainability indicators was used and contextualized further with the aid of participatory methods involving local stakeholders. A key finding was that a lack of institutional capacity to implement adequate treatment systems and provide local technical expertise, along with a lack of financial resources, prevented the WWTPs from performing optimally. The performance of the WWTPs was also affected by issues in the sewer network resulting from design problems or inadequate use. In this context there were five relevant sustainability dimensions for assessment of small WWTSs: institutional, social, economic, technical, and environmental. The list of contextualized sustainability indicators and the knowledge acquired led to the development of a sustainability assessment tool, EVAS (Evaluation of Sustainability/Evaluación de Sostenibilidad), for small WWTSs during the operational stage. The aim of the EVAS tool is to enable managers of small WWTSs and local decision-makers to assess the current status of their WWTSs and support the formulation of strategies to improve their sustainability.

Keywords: Wastewater treatment system, low and lower-middle income countries, local stakeholders, operation and maintenance, performance assessment, resource recovery, institutional dimension, sustainability indicators, sustainability assessment, EVAS tool (EVAluation of Sustainability).

LIST OF PAPERS

This thesis was developed based on the following papers, referred to in the text using Roman numerals:

I. Cossio, C., McConville, J., Rauch, S., Wilén, B.M., Dalahmeh, S., Mercado, A., Romero, A.M. (2017). Wastewater management in small towns – understanding the failure of small treatment plants in Bolivia. *Environmental Technology (United Kingdom)* 39: 1–11.
DOI: https://doi.org/10.1080/09593330.2017.1330364

II. Cossio C., Perez-Mercado L.F., Norrman J., Dalahmeh S., Vinnerås B., Mercado A. & McConville J. (2019). Impact of treatment plant management on human health and ecological risks from wastewater irrigation in developing countries – case studies from Cochabamba, Bolivia. *International Journal of Environmental Health Research (United Kingdom).*
DOI: https://doi.org/10.1080/09603123.2019.1657075

III. Cossio C., Norrman J., McConville J., Mercado A. & Rauch S. (2020). Indicators for sustainability assessment of small-scale wastewater treatment plants in low and lower-middle income countries. *Environmental and Sustainability indicators Journal* 6, 100028.
DOI: https://doi.org/10.1016/j.indic.2020.100028

IV. Cossio C., McConville J., Mattsson A., Mercado A. & Norrman J. (2020). Developing a tool for sustainability assessment of small wastewater treatment systems in low and lower-middle income countries. S*ubmitted manuscript.*

Division of work between the authors

In Paper I, Cossio, McConville, Rauch and Dalahmeh designed the structure of the paper. Cossio and Mercado collected field data in Bolivia. Cossio processed the data and Mercado contributed to the calculation of the operational parameters. Cossio and McConville were responsible for drafting the paper. Rauch revised the paper and contributed to the final version. All the authors contributed to the final revision.

In Paper II, Cossio, McConville and Perez-Mercado designed the structure of the paper. Cossio collected field data in Bolivia. Perez-Mercado carried out the risk assessment and contributed to the manuscript, primarily the sections relating to risk assessment. Cossio, McConville and Norrman performed the management assessment for the case studies. Cossio was responsible for drafting and structuring the paper. All the authors revised the paper and contributed to the final version.

In Paper III, Cossio, Norrman and McConville designed the structure of the paper. Cossio and Mercado collected field data in Bolivia. Cossio systematized the indicators and processed the data. Cossio was responsible for drafting the paper, and Norrman and McConville revised it and contributed to the final version. Rauch and Mercado contributed to the final revision.

In Paper IV, Cossio, Norrman and McConville designed the structure of the paper. All the authors contributed to developing the sustainability assessment tool (EVAS), and the majority of the Excel work was carried out by Cossio. Cossio and Mercado collected field data in Bolivia and tested the tool in Bolivia. Cossio was responsible for drafting the paper. Norrman, McConville, Mattsson and Mercado revised the paper and contributed to the final version.

Publications and other work not appended

The author has contributed to the following work and publications, which are not appended to the thesis:

- Cossio, C., Norrman, J. McConville J., Mattsson, A., Mercado, A. (2020). EVAS (EVAluation of Sustainability/EVAluación de Sostenibilidad) - a sustainability assessment tool for small wastewater treatment systems, ver 1.0.

  https://research.chalmers.se/publication/?created=true&id=0729f196-e9ee-4e44-9b2b-1c987e7f3dc6
- Cossio C., McConville J., Rauch S., Mercado A. (2017). *Wastewater management in developing countries: Bolivia case studies*. IN: Shaw, R.J. (ed). Local action with international cooperation to improve and sustain water, sanitation, and hygiene (WASH) services: Proceedings of the 40th WEDC International Conference, Loughborough, UK, 24-28 July 2017, Paper 2776, 4pp.

  https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/31445
- Helgegren, I., Rauch, S., Cossio, C., Landaeta, G., McConville, J. (2018). Importance of triggers and veto-barriers for the implementation of sanitation in informal peri-urban settlements - The case of Cochabamba, Bolivia. *PLoS ONE* 13 (4): 1–17.
  https://doi.org/10.1371/journal.pone.0193613
- Mercado, A., Cossio, C., Coronado, O. (2015). *Diagnosis of infrastructure and water quality for the drinking water distribution system in Tiraque, Cochabamba, Bolivia*. Paper presented at the 16th Bolivariano Congress of Sanitary Engineering, Environment and Renewable Energies - AIDIS, Santa Cruz, Bolivia, 15-17 October 2015.
- Ustariz-Zabalaga, K., Cossio, C., Mercado, A. (2018). *Solar disinfection of domestic wastewater using a compound parabolic solar concentrator and a batch reactor*. Paper presented at the 17th Bolivariano Congress of Sanitary and Environmental Engineering-ABIS, Cochabamba, Bolivia, 29-31 August 2018.
- Mercado A., Cossio C., Copa M. (2019). *Efficiency and management of small domestic wastewater treatment plants in Cochabamba, Bolivia.* Paper presented at

the 1st International Congress of Integral Water Management - CIGIA, Cochabamba, Bolivia, 2-4 October 2019.

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Gothenburg, May 2020

Claudia Cossio

LIST OF ABBREVIATIONS

The following notations are used in the main text of the thesis:

BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
DALY	Disability Adjusted Life Years
EVAS	EVAluation of Sustainability/EVAluación de Sostenibilidad
FC	Faecal coliforms
HH	Helminth eggs
HLR	Hydraulic loading rate
HRT	Hydraulic retention time
Log10	Logarithmic reduction
$N\text{-}NH_4$	Ammonium
$N\text{-}NO_3$	Nitrate
OVL	Organic volumetric load
QMRA	Quantitative Microbial Risk Assessment
SDG	Sustainable Development Goal
TSS	Total Suspended Solids
TN	Total Nitrogen
TP	Total Phosphorus
UASB	Upflow anaerobic sludge blanket
WHO	World Health Organization
WWTP	Wastewater treatment plant
WWTS	Wastewater treatment system

TABLE OF CONTENTS

1 INTRODUCTION

This chapter includes a presentation of the background to the thesis, a definition of the aim and objectives, and a description of the scope and limitations.

1.1 Background

Achieving sustainable global management of basic sanitation services, which involves the collection and safe treatment of wastewater, reducing contamination, and increasing the reuse of recovered resources, is a formidable challenge. Sustainable Development Goal 6, launched by the United Nations in January 2016, aims to ensure the availability and sustainable management of water and sanitation for all (UN, 2016a; Brinkmann and Garren, 2018). Progress made regarding wastewater treatment within the global indicator framework for the SDGs is being measured using indicator 6.3.1 – proportion of wastewater safely treated (UN, 2018b). The 2015 baseline estimated that in low and lower-middle income countries the percentages of treated wastewater were 8% and 28%, respectively. The goal behind halving the proportion of untreated wastewater is to increase these figures to 54% and 64% by 2030 (WWAP, 2017). In addition, the accelerated urbanization process that is predicted to occur most rapidly in low and lower-middle income countries demands the introduction and operation of basic services (UN, 2018a). This ongoing urbanization is a challenge to the achievement of SDG 6.3.1, as small towns that are making the transition from rural communities into urbanized cities often lack the infrastructure or management capacity for wastewater collection and treatment. Consequently, greater effort is required in these regions to reach these targets, especially in countries with low coverage due to limitations in available treatment technology, monitoring data, a lack of regulations for safe reuse, and a lack of planning for sustainable wastewater management (WHO, 2018; Razzolini et al., 2020; de Carvalho et al., 2019). Sustainable wastewater management is important, not only to safeguard human health and avoid environmental degradation, but also for resource recovery and reuse (Friedler et al., 2013). It therefore involves the need to shift from the paradigm of conventional wastewater treatment with an end-of-pipe solution to a more integrated approach, including resource recovery and safe reuse (Chamberlain et al., 2014). This is in line with a resource-oriented circular economy and ecosystem service paths for sustainable resource cycles (e.g. water, nitrogen, phosphorus, carbon) (Masi et al., 2018; Barquet et al., 2019; Molina-Moreno et al., 2017).

Contamination of waterbodies in Latin America and the Caribbean due to untreated wastewater has worsened since 1990, reaching severe levels in 2010 (i.e. monthly concentrations above 8 mg/L of biochemical oxygen demand (BOD) in-stream) and the prediction at that time was that it would increase over time, making it necessary to find strategies to improve the situation (UN, 2016b). Latin America is a region where most of the wastewater treatment plants (WWTPs) are small, with operational flows in the 5-25 L/s range (Noyola et al., 2012). Small WWTPs in low and lower-middle income countries in general reveal low performance, mainly due to a lack of adequate operation and maintenance of the infrastructure (Singhirunnusorn and Stenstrom, 2009; Noyola et al., 2012). Lack of technical capacity (Ujang and Buckley, 2002), lack of financial resources, and lack of monitoring are other factors that also stand in the way of an efficient wastewater treatment systems (WWTS) (Massoud et al., 2009; Noyola et al., 2012). Planners in low and lower-middle income countries are thus challenged with these factors when selecting appropriate technology as a means of ensuring optimal performance (Bdour et al., 2009; Brissaud, 2007; Mara, 2013). In addition, local and national authorities must ensure that monitoring systems are in place, along with clear regulations for reuse in order to protect human health and implement sustainable reuse practices (Razzolini et al., 2020; Kulakov, 2015).

Sustainability studies dealing with WWTPs in high and upper-middle income countries mainly raise environmental concerns regarding effective use of natural resources and protection of the environment, although social and economic aspects are also considered as an integral part of sustainable wastewater treatment systems (Kalbar et al., 2016; Sweetapple et al., 2015; Moreno et al., 2017). On the other hand, wastewater treatment practices in low and lower-middle income countries still face technical and economic challenges, and the social component is highlighted as the key to the sustainability of services (Hranova, 2010; Iribarnegaray et al., 2015; Padilla-Rivera et al., 2016). The different setting in low and lower-middle income countries requires greater understanding of the specific challenges that exist and identification of indicators relevant to achieving sustainable wastewater treatment from a planning and operation point of view. If progress is to be made, it is important to develop tools that can be easily applied by local stakeholders in an effort to assess and improve the sustainability of WWTSs by adopting a holistic approach.

1.2 Aim and objectives

The overall aim of this thesis is:

> *To acquire greater knowledge and understanding of factors that affect the sustainability of small wastewater treatment systems (in Bolivia or other low and lower-middle income countries), in order to enable a sustainability assessment to be made of the current operational status in an effort to help decision-makers make improvements, with the ultimate aim of achieving more sustainable systems.*

The specific objectives are:

i. To identify critical aspects affecting the functionality and management of small WWTPs in Bolivia, as well as gain an understanding about how user perception may affect service delivery.

ii. To analyse how management practices at small WWTPs may impact on public health risks related to reuse of wastewater for irrigation purposes.

iii. To identify, contextualize and formulate indicators that are relevant and useful for sustainability assessment of small WWTPs in low and lower-middle income countries.

iv. To develop a method and a tool for sustainability assessment of small WWTSs in low and lower-middle income countries in order to help managers identify management strategies and actions to improve sustainability

1.3 Scope

The specific objectives of this thesis are investigated by means of four main studies, presented as four papers, listed below:

Paper I – Wastewater management in small towns – understanding the failure of small treatment plants in Bolivia.

Paper II – Impact of treatment plant management on human health and ecological risks from wastewater irrigation in developing countries – case studies from Cochabamba, Bolivia.

Paper III – Indicators for sustainability assessment of small-scale wastewater treatment plants in low and lower-middle income countries.

Paper IV – Developing a tool for sustainability assessment of small wastewater treatment systems in low and lower-middle income countries.

In addition, a smaller study on the perception of the users regarding the WWTSs is included in the thesis, also related to the specific objective i) above.

The research questions formulated for the development of the studies, and the outcomes obtained in the studies, are set out in Table 1-1.

Table 1-1. Research questions formulated for development of the thesis, the outcomes obtained, and appended papers.

RESEARCH QUESTIONS	OUTCOMES	PAPER
Why do small WWTPs remain a challenge in low and lower-middle income countries?	Performance assessment of five small WWTPs and findings relating to management limitations.	I
What is the perception of users in relation to the service of wastewater management, i.e. sewer network and the treatment at the WWTP?	Understanding on how the users perceive both collection and treatment services, identification of issues, benefits, level of awareness and public acceptance.	*
What is the impact of the management of small WWTPs on human health and the ecological risks from wastewater irrigation in low and lower-middle income countries?	Determination of how the management and technology employed at five small WWTPs impact on human health and ecological risks arising from wastewater irrigation practices.	II
Which are the most common sustainability indicators in the literature for assessing the sustainability of small WWTPs, and which indicators are suitable in the specific context of low and lower-middle income countries?	Systematization of 40 sustainability indicators from a literature review and screened to: i) a list of 12 standard sustainability indicators (mentioned in 33% or more of the studies reviewed) ii) a list of 27 contextualized sustainability indicators using input from local stakeholders and experts: 26 indicators matched with the initial list of 40 indicators and one new indicator formulated using local input.	III

How can the current operational status of small-scale WWTPs in (Bolivia/low and lower-middle income countries) be assessed in practice by local stakeholders, including all relevant sustainability factors and supporting management actions aimed at sustainability?	EVAS tool to assess the sustainability of small wastewater treatment systems, including generic and local context factors, and tested in two case studies.	IV

* The main results from the study are presented in the Results section 4.2.

The thesis contains six chapters. The remainder of the thesis is structured as follows:

- Chapter 2 presents the theoretical background to wastewater treatment, small wastewater treatment plants, and sustainability.
- Chapter 3 describes the methods used for data collection and assessment in the four papers.
- Chapter 4 contains a summary of the main findings from the four appended papers.
- Chapter 5 includes a discussion of the critical findings regarding the sustainability of wastewater treatment in the context of this study, as well as the method and tool developed for making sustainability assessments.
- Chapter 6 contains the overall conclusions, recommendations, and work in the future.

2 THEORETICAL BACKGROUND

This chapter presents the theoretical background of the thesis. It contains an explanation of the theory and concepts related to wastewater treatment, small wastewater treatment systems, and sustainability.

2.1 Wastewater treatment systems

The provision of sustainable sanitation services involves assuring a functional value chain, starting at household level and proceeding through to final disposal or reuse (Mehta and Mehta, 2013). In general, the value chain includes five functional steps: user interface; collection; transportation; treatment; reuse and/or disposal (Tilley et al., 2014). A range of technologies is available that can be used in each functional step in the chain. A sanitation system thus results from a combination of these functional steps and the input/output materials that flow through the system (e.g. raw wastewater and sludge produced). This system not only requires effective management but also operation and maintenance to ensure optimal and sustainable functionality.

Wastewater is typically separated into two categories, domestic and industrial. Domestic wastewater comes from households and commercial/public facilities as a result of domestic activities, while industrial wastewater is mostly made up of industrial waste (Metcalf et al., 2014). Domestic wastewater includes two distinct streams: blackwater and greywater. Sources for blackwater are urine, faeces, flush water, and toilet paper (if applied). Greywater sources include water from showers, bathtubs, bathroom washbasins, kitchen sinks, laundry facilities, dishwashers, and washing machines (Friedler et al., 2013). Domestic wastewater is collected at the households or at commercial/public facilities, and can be treated on-site or transported for treatment off-site (WHO, 2018). Treatment typically includes pre-treatment and then treatment at primary, secondary and tertiary level. The pre-treatment unit removes large solids, grit, and grease from raw wastewater. This unit is critical if the ensuing treatment units are to work adequately without becoming clogged or saturated too easily. Primary treatment removes part of the suspended solids and organic matter from the wastewater. It can be raised to the advanced primary treatment level by adding chemicals or filtration processes. Secondary treatment removes dissolved or suspended biodegradable organic matter and suspended solids. Tertiary treatment removes the residual suspended solids, nutrients, and pathogens through disinfection.

2.1.1 Characterization of domestic wastewater

The composition of the constituents in wastewater varies according to local conditions and is usually characterized using physical, chemical, and biological parameters. The list of parameters used to characterize wastewater can be extensive. Typical parameters used to evaluate the performance of the wastewater treatment systems are Total suspended solids (TSS), Biochemical oxygen demand (BOD), Chemical oxygen demand (COD), Total Nitrogen (TN), Total Phosphorus (TP) and Faecal coliforms (FC) (Von Sperling and Augusto De Lemos Chernicharo, 2002; Özkan et al., 2012). The main purpose of wastewater treatment is to reduce or inactivate pathogenic microorganisms that can cause diseases in humans (Friedler et al., 2013; Rahmani and Anuar, 2019). Suspended solids and oxygen-demanding substances (e.g. organic matter and ammonia) must be reduced to avoid lowering the quality of waterbody recipients (Voulvoulis, 2018). Removal of nutrients (e.g. nitrogen and phosphorus) is also needed to protect waterbodies from eutrophication (Meena et al., 2019). However, if the effluent is reused in agriculture, the nutrient content may be beneficial, although pathogenic microorganisms and toxic compounds, such as heavy metals or pharmaceuticals, should be removed (Qadir and Scott, 2010; Hamilton et al., 2007). The strength of the wastewater can be defined by the content of its constituents, and it can be categorized as high, medium, or low strength. Typical values are shown in Table 2-1.

Table 2-1. Typical values for wastewater characterization, low-medium-high strength.

Parameter	Units	Low - medium - high strength[1]	Typical values for Latin America[2]
TSS	mg/L	130 - 195 - 389	264
BOD_5	mg/L	133 - 200 - 400	244
COD	mg/L	339 - 508 - 1,016	557
FC	CFU/100 ml	10^3-10^5 ; 10^4-10^6; 10^5-10^8	-

[1]Metcalf et al., 2014; [2]Noyola et al., 2012

Regulations for discharge are different in each region and country. Table 2-2 shows a comparison of the limits for BOD, TSS and FC for Latin America and the Caribbean, and Bolivia.

Table 2-2. Standard regulations for discharge into waterbodies for Latin America and the Caribbean, and Bolivia.

Parameters	Latin America and the Caribbean[1]	Bolivia[2]
BOD	30 mg/L	80 mg/L
TSS	30 mg/L	60 mg/L
FC	1000 MPN/100 ml	1000 MPN/100 ml

[1]Noyola et al. 2012; [2]MMAyA, 1995

2.1.2 Wastewater management systems

Wastewater management includes all aspects related to planning, finances, promotion, construction, operation and regulation in order to handle wastewater from origin to reuse or final disposal (Robbins and Ligon, 2014; Friedler et al., 2013). There are two main types of wastewater management systems – centralized and decentralized. Centralized wastewater treatment involves treating wastewater and sometimes additional stormwater from large urban or peri-urban areas. Centralized systems can include or not include the collection system, and treatment is carried out at a central plant for further reclamation or discharge into the environment. Decentralized wastewater treatment systems are run on a small-scale to treat wastewater from individual properties, clusters of properties, villages, or small towns (Tilley et al., 2014; Reckerzügel et al., 2009). They include collection, treatment and reuse or disposal, carried out at the same location or closer to the generation point (Tchobanogious et al., 2004). These systems are considered to be a complement to the centralized wastewater treatment systems and can vary from onsite systems to satellite treatment systems (Van Afferden et al., 2015; Tchobanogious et al., 2004)

2.1.3 Wastewater from waste to resource

Nowadays the need to implement integrated solutions to recover resources from wastewater from a circular economy perspective is critical for sustainability (Guest et al., 2009; Larsen et al., 2009). This is particularly the case when finite resources such as phosphorus can be captured for productive use in industry and agriculture (Mihelcic et al., 2011). In low and lower-middle income countries the practice of wastewater reuse is common, and the potential benefits of water containing nutrients (e.g. nitrogen, phosphorus and potassium) have been recognized, particularly in regions affected by water scarcity, climate change, and environmental contamination, such as eutrophication of waterbody recipients (Cornejo et al., 2013). A range of resources, such as carbon, micronutrients, and energy, can be recovered from wastewater treatment plants and reused. Organic carbon sequestration that enhances the quality of soils degraded by intensive agricultural practices is one of the benefits, as is reducing CO_2 emissions into the atmosphere (Masi et al., 2018). Nitrogen and phosphorus are highly valued in the market and their availability as a resource is limited (Barquet et al., 2019; Meena et al., 2019).

Despite the positive effects of using the resources recovered from wastewater (e.g. water, nutrients, or energy), there are still public health risks associated with this practice in low and lower-middle income countries (Qadir et al., 2010). In this context, health risks exist due to contamination as a result of wastewater irrigation practices (Hamilton et al., 2007; Bos et al., 2010). This is a source of concern as most WWTPs in low and lower-middle income countries are not designed to remove the pathogenic load in the raw wastewater that reaches the WWTPs (Bos et al., 2010). Health risks are commonly associated with pathogens, such as bacteria, helminth eggs, and viruses (Gumbo et al., 2010; Moazeni et al., 2017; Mara and Sleigh, 2010; Qadir et al., 2010). Ecological risks are associated with eutrophication effects on water sources due to accumulation of nutrients such as nitrogen and phosphorus in the soil (Uzen et al., 2016; Jaramillo and Restrepo, 2017). Resource recovery can be beneficial, not only environmentally but also financially. However, more advanced technologies might be required to extract resources (e.g. nutrients, biomethane, biofuel, or bioelectricity) (Meena et al., 2019). Consequently, planners in low and lower-middle income countries must take this into consideration when introducing a new WWTS with the aim of resource recovery.

2.1.4 Wastewater treatment in low and lower-middle income countries

Wastewater treatment in low and lower-middle-income countries is carried out in both centralized and decentralized systems. The technologies used in these systems must take into account local available resources for their functionality (Singhirunnusorn and Stenstrom, 2009). The accelerating growth in urbanization will challenge the provision of adequate wastewater treatment, especially in small towns where the infrastructure, financial resources, and managerial capacity are usually limited (Caplan and Harvey, 2010; Sundaravadivel and Vigneswaran, 2003; Singh et al., 2015).

2.1.5 Small wastewater treatment plants

In the case of small WWTPs it is common in low and lower-middle income countries for particular management challenges to arise, such as low performance, due mainly to a lack of adequate operation and maintenance of the infrastructure (Singhirunnusorn and Stenstrom, 2009; Noyola et al., 2012). Other factors that obstruct the efficient operation of a WWTP are lack of technical capacity (Ujang and Buckley, 2002), lack of financial resources, and lack of monitoring (Massoud et al., 2009; Noyola et al., 2012). These small plants can be greater in number in comparison to large-scale WWTPs, which when combined actually treat a larger volume of wastewater (Libralato et al., 2012; Noyola et al., 2012). As these small WWTPs are usually found in villages or small towns, they are not always included in the national statistics (Malik et al., 2015). There is thus a lack of information regarding their number, the flow levels that are treated, and their performance.

One of the main reasons for the failure of small WWTPs in low and lower-middle-income countries is the lack of financial resources to implement optimal operation and maintenance (Usha Rani and Vasumathi, 2013; Brunner et al., 2018). In addition, small WWTPs can face challenges in the form of inappropriate technology (Mara, 2013; Bdour et al., 2009; Brissaud, 2007; Zurita et al., 2012), and lack of expertise, with resulting poor operation and maintenance practices (Singhirunnusorn and Stenstrom, 2009; Ujang and Buckley, 2002; Friedler et al., 2013). The inadequate performance of the small WWTPs could result in them failing to comply with standards and regulations (Noyola et al., 2012; Bunce and Graham, 2019; Friedler et al., 2013). The extent to which small, poorly performing WWTPs with insufficient wastewater treatment are impacting on public health and the environment may be underestimated. This could be attributed to the large number of such facilities and the lack of monitoring data on their performance to assess whether or not they are complying with the limits set out in the standards (Noyola et al., 2012; Bunce and Graham, 2019).

2.1.6 Small wastewater treatment plants in Latin America and Bolivia

In Latin America and the Caribbean, a small wastewater treatment plant typically treats flows of 432 - 2,160 m^3/d and a very small wastewater treatment plant treats flows less than 432 m^3/d (Noyola et al., 2012). The most common technologies employed for wastewater treatment in Latin America and the Caribbean (i.e. 80% from a sample of 2,734 WWTPs identified) are stabilization ponds, activated sludge, and upflow anaerobic sludge blanket (UASB) reactors (Noyola et al., 2012). In Bolivia, an inventory prepared by the national government in settlements with more than 2,000 inhabitants revealed that the most common technologies used were stabilization ponds (56%), Imhoff tanks (20%), septic tanks (11%), biofilters (6%), and UASB (1%) (MMAyA, 2013). In Bolivia, these technologies are used at the primary and secondary treatment levels and thus mainly remove suspended solids and organic matter. Both studies at the regional level (i.e. Latin America) and the national level (i.e. Bolivia), found similar constraints, resulting in poor performance of WWTPs, such as lack of adequate operation and maintenance, technical capacity, and financial resources (Noyola et al., 2012; MMAyA, 2013).

2.2 Sustainability of wastewater treatment plants

Sustainable development is defined as “Development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs”. This definition was formulated in 1987 in the Brundtland Report, prepared within the framework of the United Nations World Commission on Environment and Development (WCED, 1987). Based on this well-known definition, a number of sustainability concepts have emerged. However, the task of linking theorical concepts to practical applications is still ongoing (White, 2013).

In general, a sustainable wastewater management system includes a functional collection system, sustainable treatment, a recovery system for resources, an appropriate economic structure, and legislation to protect the environment and public health (Rahmani and Anuar, 2019). The concept of sustainability in low and lower-middle income countries is often expanded beyond the traditional environmental, economic, and social dimensions. Laugesen et al. (2009) state that a sustainable wastewater management system must include efficient systems for wastewater collection and treatment, with integrated low-energy consumption, reuse practices, or safe discharge into the environment, and coupled with an appropriate organizational and financial structure (Laugesen et al., 2009). Singhirunnusorn and Stenstrom (2009) state that a sustainable WWTS should be technologically appropriate in the local context in terms of social and environmental acceptability, and institutional and financial feasibility (Singhirunnusorn and Stenstrom, 2009). The Sustainable Sanitation Alliance (SuSanA) provides a holistic definition of sustainable wastewater management, i.e. a system that reduces depletion of natural resources and environmental deterioration, protects human health, and is technically and institutionally suitable, socially acceptable, and financially viable in the long term (Andersson et al., 2016)

2.2.1 Sustainability dimensions and indicators

Sustainability assessment of wastewater treatment systems commonly includes the environmental, economic, and social dimensions (Balkema et al., 2002; Ren and Liang, 2017). Sustainability studies implemented in high and upper-middle income countries generally raise environmental concerns regarding the effective use of natural resources and protection of the environment, although social and economic aspects are also considered to be an integral part of sustainable wastewater treatment systems (Kalbar et al., 2016; Sweetapple et al., 2015; Moreno et al., 2017). On the other hand, wastewater treatment practices in low and lower-middle income countries still face technical and economic challenges, and the social component is key to the sustainability of wastewater services (Hranova, 2010; Iribarnegaray et al., 2015; Padilla-Rivera et al., 2016).

2.2.2 Sustainability assessment

Sustainability assessments are generally based on the original conceptualization of sustainability using the three typical dimensions, i.e. environmental, economic, and social (Wallis et al., 2011). A sustainability assessment can be a tool, a method, or a process aimed at supporting decision-makers and policy-makers in identifying any necessary actions that need to be taken to achieve sustainability (Pope et al., 2017; Sala et al., 2015; Singh et al., 2012; Villeneuve et al., 2017). A sustainability assessment should provide decision-makers with information on the key elements that contribute to the sustainability of a specific system (Brinkmann and Garren, 2018). Making a sustainability assessment can be complex as it must be able to combine aspects from the different dimensions, thus making it a multidisciplinary task (Villeneuve et al., 2017).

The development of a sustainability assessment tool and the selection of indicators can take place by combining two approaches: the 'top-down' approach and the 'bottom-up' approach (Singh et al., 2012; Reed et al., 2005; Reed et al., 2006). The 'top-down' approach is adopted at the expert level with theoretical concepts and standard sustainability indicators. The 'bottom-up' approach requires the involvement of community stakeholders to provide locally specific input and validate relevant sustainability indicators. A combination of these two approaches is beneficial when aiming to develop a practical assessment tool. Thus, in order to develop such a tool, it is important to involve stakeholders in a transdisciplinary way, facilitating the build-up of knowledge and identification of solutions (Brinkmann and Garren, 2018; Bell and Morse, 2004). As a result, the sustainability assessment tool applied in practice will support these local stakeholders as they plan and/or improve the current status of the systems with the aim of making them more sustainable (Clarkson et al., 2010; Dhinadhayalan and Nema, 2012; Brunner et al., 2018).

Including a large number of sustainability indicators in the assessment allows for a holistic approach to be adopted and supports the use or adaptation of the tool in a similar context (Domínguez et al., 2019). Normalization methods are often applied to transform different indicator units to make them comparable (Molinos-Senante et al., 2014; Böhringer and Jochem, 2007). Aggregation methods can then be used to obtain a functional relationship and calculate a final index, and weighting methods can be applied to differentiate relevance among indicators (Böhringer and Jochem, 2007). The weighting supports decision-making regarding the trade-off between indicators, thus achieving a balance between all the desirable attributes used in the assessment (Balkema et al., 2002). Making a holistic assessment often involves dealing with uncertainties that can be minimized using a probabilistic approach or applying a sensitivity analysis (Sala et al., 2015; Böhringer and Jochem, 2007; Palme et al., 2005). Complex methods will assure more accurate results, but may discourage practical applications. An iterative process for developing practical tools can therefore be applied by testing the tool in a real context and making adjustments in relation to scientific knowledge (Benavides et al., 2019).

3 METHODS

This chapter includes a description of the research design, as well as a presentation of the case study areas, the methods used for data collection in the field, and the assessment methods applied.

3.1 Research design

A case study approach (Yin, 2014) was applied in the research design to answer the research questions formulated in the thesis. Site and context-specific data were collected in the field, either at the WWTPs or during meetings with local stakeholders and by a semi-structured interview among users. Nine case studies are included in this thesis: six small towns with a population ranging from 2,000-10,000, and three villages with a population below 2,000 (referred to as very small towns in this thesis). The aim of the field research was to understand the local context (Stake, 1995) and relate this to the existing theoretical knowledge of sustainability of wastewater treatment (Flick, 2014). A tool was developed for sustainability assessment of wastewater treatment within the context of the case studies, applying the theoretical and empirical knowledge acquired from the first three studies. The developed tool was tested in two of the case studies included in this thesis. A schematized description of the overall research design applied is presented in Figure 3-1. The case study areas and details of each method are presented in the following sections.

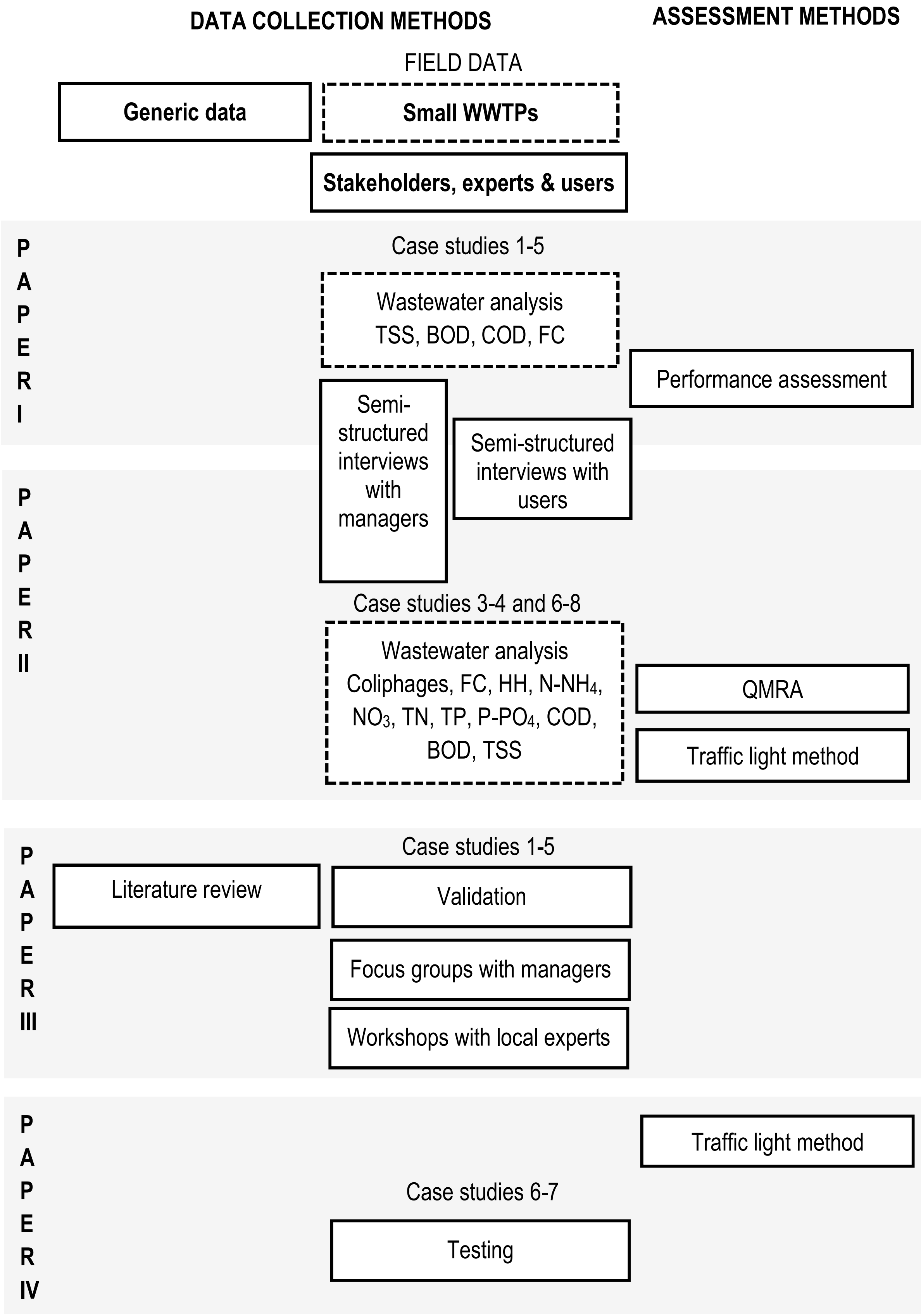

Figure 3-1. Overview of the research design and the methods used in the thesis, specified for each paper.

3.2 Case study areas

The field studies were conducted at small wastewater treatment plants (WWTPs) located in Bolivia, more specifically in the Cochabamba Valley in the Andes mountain range. According to the categorization of countries by income, Bolivia is considered to be a lower-middle income country (World Bank, 2018). To investigate the performance of small WWTPs, a number of small towns and villages in the study area were selected. A small town is defined as a settlement with a mix of urban and rural characteristics (Caplan and Harvey, 2010). In Bolivia, a settlement is considered to have urban characteristics when it has a population of more than 2,000 (O'Hare and Rivas, 2007), and becomes a city when it has a population of over 10,000(The World Bank, 2017). A small town in Bolivia is therefore a settlement with mixed urban-rural characteristics and with 2,000-10,000 inhabitants, and a village is a settlement with fewer than 2,000 inhabitants.

3.2.1 System boundaries

In Cochabamba, the municipalities are responsible for the provision of basic services: drinking water systems (i.e. catchment system, network pipes and taps) and wastewater services (i.e. sewer network and wastewater treatment plant). Once a basic service system is established in a small town or village, it is placed under the management of a local organization or association, usually overseen by a board made up of members of the organization or association. The board runs the services either by hiring staff, as is the case in small towns, or by delegating the tasks to members of the board, as is the case in many villages. Figure 3-2 shows how basic service systems work in the municipalities, including system input sources and output products, as well as the recipients of these products. In this thesis the system boundaries of the wastewater treatment system (i.e. collection system and treatment) are marked with a dashed line in Figure 3-2.

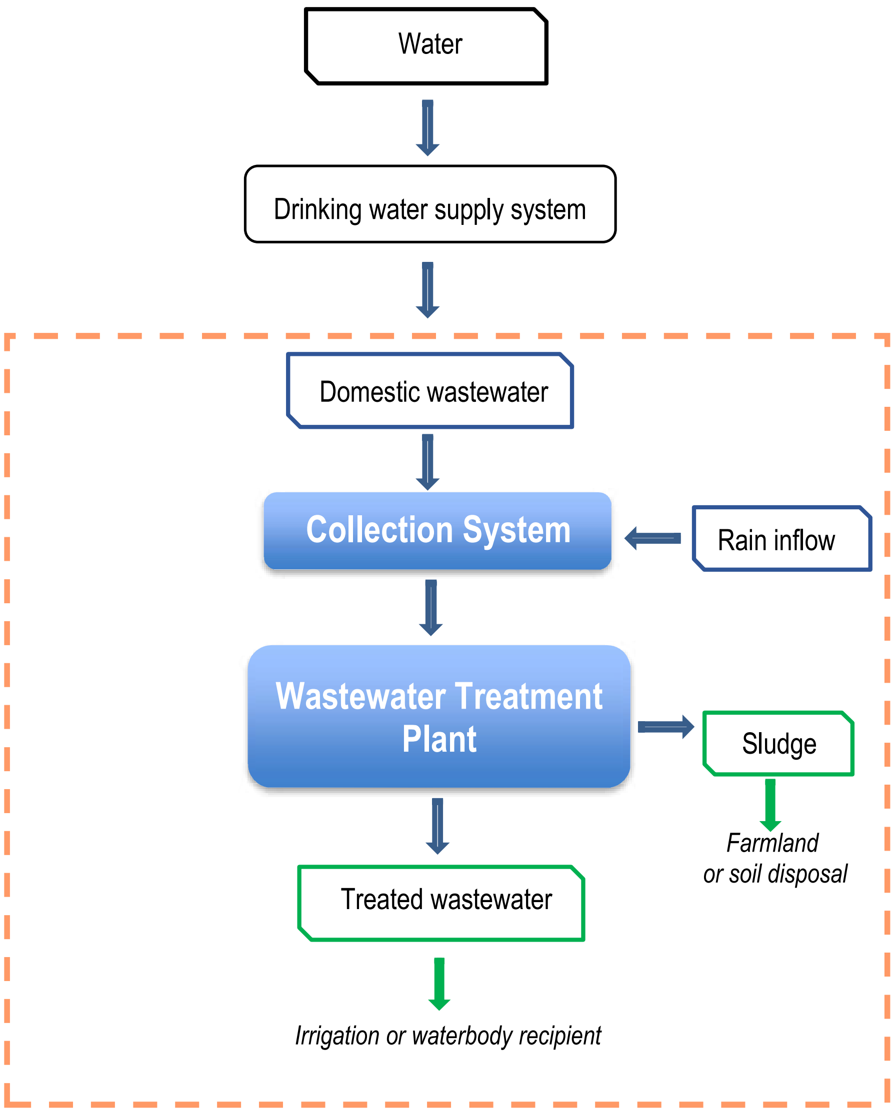

Figure 3-2. Illustration of the basic service components in the case studies. The orange dashed line delimits the system being studied: the main components are in the blue boxes (i.e. collection system and wastewater treatment plant), the boxes outlined in blue contain the inputs (i.e. domestic wastewater and rain inflow) and the boxes outlined in green contain the outputs of these components (i.e. treated wastewater, and sludge).

3.2.2 Identification of stakeholders and experts

A further stage in the field research was the identification of the stakeholders involved in the management of wastewater treatment in the areas included in the study. The aim of the identification process was to select key stakeholders in order to conduct interviews and gather information. The main stakeholders identified were managers of the WWTPs, and staff at the decision-making level (i.e. municipal, regional and national authorities). Managers included board members and/or staff hired to manage the WWTPs. Among the population being served, the users (i.e. householders, commercial and public institutions) and farmers who reuse the treated wastewater were identified as the groups that are beneficiaries of the service. In addition, local experts participated in the contextualization of sustainability indicators. Stakeholders, roles, how data was collected from each group, and how it was used in the thesis are shown in Table 3-1.

Table 3-1. Stakeholders, roles, data collection, and use of the data in the thesis.

Stakeholders	Role	Data collection	Use of the data in the thesis*
Managers of the WWTPs (board members and staff)	Management of the WWTP	Semi-structured interview with the manager	Papers I, II and IV
		Focus groups made up of the managers and board members	Papers III and IV
Users	Customers who pay for and use the service	Semi-structured interview	Paper IV
Farmers	Reuse of the treated wastewater	Semi-structured interview	Papers II and IV
Staff from the municipal authority	Investment and assistance (e.g. equipment or technical advice)	Informal interview	Paper IV
Staff from the regional authority	Monitoring	Informal interview	Paper IV
Representatives from the Ministry of Water and Environment: SENASBA (National Service for the Sustainability of Basic Sanitation Services)	Technical assistance and strengthening for institutions that provide basic services (e.g. water and sanitation)	Workshop	Paper IV
Local experts from the technical and social fields	Provide input in the formulation of local sustainability indicators	Workshop	Papers III and IV

*Paper IV builds on all the information collected during the course of this thesis work.

3.2.3 Criteria for selecting case study areas

The area of study was the Cochabamba Valley in Bolivia, where six small towns and three villages were selected for inclusion in the study, all located in the urbanized part of the municipalities. Even though the focus of the study was small towns, three villages were included to acquire an understanding of the transition between the rural context and the urban-rural context with regard to wastewater management. Apart from the size of the population, a further criterion for selecting the case study areas was use of treatment technologies that are commonly used in Bolivia i.e. stabilization ponds, Imhoff tanks, biofilters, and UASB reactors (MMAyA, 2013). After the field visits and establishing contact with local stakeholders, nine case study areas with WWTPs were identified. A description of the WWTPs included in the nine case studies is presented in Table 3-2.

Table 3-2. Description of the WWTPs studied. Codes for the nine case studies. Codes for the WWTPs in the four papers (P-I, P-II, P-III and P-IV); location of the WWTPs (L) and Municipality (M); population equivalent served; process units included in each WWTP, and level of treatment specified: primary treatment (PT), secondary treatment (ST), and tertiary treatment (TT).

Code for case study	Code in the papers	Location and municipality	Population equivalent	Process units at WWTP
CS1	P I: STP1 P III: WWTP1	Tiraque (L) Tiraque (M)	4,660	- Pre-treatment - 1 Imhoff tank (PT) - 2 biofilters (ST)
CS2	P I: STP2 P III: WWTP3	Colomi (L) Colomi (M)	6,155	- 2 Imhoff tanks (PT)
CS3	P I: STP3 P II: Case 3-P	Tarata (L) Tarata (M)	7,000	- Pre-treatment - 2 anaerobic ponds (PT) - 2 facultative ponds (ST) - 4 maturation ponds (TT)
CS4	P I: VSTP1 P II: Case 5-I P III: WWTP2	Virvini (L) Tiraque (M)	670	- 1 Imhoff tank (PT)
CS5	P I: VSTP2 P III: WWTP4	Chamoco (L) Colomi (M)	825	- Pre-treatment - 2 Imhoff tanks (PT)
CS6	*	Millu Mayu (L) Tiraque (M)	40	- Septic tank - Biofilter
CS7	P II: Case 1-UFP P IV: Case study 1	El Paso (L) El Paso (M)	3,344	- Pre-treatment - 1 UASB reactor (PT) - 2 Biofilters (ST) - 1 Maturation pond (TT)
CS8	P II: Case 2-UF P IV: Case study 2	Cliza (L) Cliza (M)	7,980	- Pre-treatment - 5 UASB reactors (PT) - 10 Biofilters (ST)
CS9	P II: Case 4-I	Ucureña (L) Cliza (M)	3,500	- Pre-treatment - Imhoff tank (PT)

p.e. = population equivalent, i.e. the ratio between the sum of the pollution load produced during a 24-hour period by institutions (i.e. schools or health centres) and the individual load produced by one person in a household.
* Investigation carried out in this case study is included in the Results section 4.2.

3.3 Methods for data collection

3.3.1 Wastewater analyses

The influent and effluent were sampled at eight WWTPs (CS1 – CS5 and CS7 – CS9), and the parameters required for each study were analysed. The sampling campaigns were planned and agreed in advance with local managers to ensure access to the WWTPs and were then sent to the laboratory at Centro de Aguas y Saneamiento Ambiental (CASA) at Universidad Mayor de San Simón in Cochabamba, Bolivia for analysis. The parameters analysed in the influent and effluent of the WWTPs were: Total suspended solids (TSS), Biochemical oxygen demand (BOD), Chemical oxygen demand (COD), Faecal coliforms (FC), Coliphages, Helminth eggs (HH), Total nitrogen (TN), Ammonium ($N\text{-}NH_4$), Nitrates (NO_3), Total phosphorus (TP) and Phosphate ($P\text{-}PO_4$). Table 3-3 presents the parameters and methods used for the analysis. The type of sampling used was a grab sample as the WWTPs studied did not have auto-samplers installed. The WWTP in CS6 could not be sampled as regularly as the other WWTPs as only a few users were connected and at times there was no flow at the inlet. Table 3-3 shows the parameters and methods used for the analysis.

Table 3-3. Parameters and methods used for the analyses

Parameter	Standard Method[1]
TSS	2540 B, C & calculation[1]
BOD	5210 B[1]
COD	5220 B[1]
TN	4500-Norg B[1]
$N\text{-}NH_4$	4500-NH_4 D[1]
$N\text{-}NO_3$	4500 NO3-D[1]
Total P	2500-P-C[1]
$P\text{-}PO_4$	4500 P-D[1]
Faecal coliforms	9222 D[1]
Coliphages	9230 C[1]
Helminth eggs	NMX-AA-113-SCFI[2]

[1] Standard methods (APHA, 2005)

[2] Mexican Secretary of Commerce and Industrial Development, 2012.

The monitoring data on the performance of the technologies at the WWTPs were implemented in eight of the case studies (CS1 – CS5 and CS7 – CS9). The collection of technical data also included flow measurements. In those cases where infrastructure plans were not available, the size of the treatment units was measured in the field (i.e. width, length and depth). These data were used to calculate the actual operational parameters of the treatment process units. Observations made during the field study visits also contributed to the pool of information as part of the effort to understand the context in which small WWTPs were functioning.

3.3.2 Semi-structured interviews

Semi-structured interviews with the managers of the nine WWTPs were conducted to collect information (Flick, 2014). The aim behind interviewing managers was to collect technical data on the number of users covered by the services, as well as the functioning and monitoring of the technologies and management practices. Questions were posed regarding operation and maintenance tasks, staff available for these activities, and their technical capability. Information was collected about the training received, the manuals available for the management of the WWTPs, work environment safety, and available tools. Financial information was gathered about costs for operation and maintenance, and service tariffs. Information was also gathered about reuse practices for the effluent from the WWTPs. The semi-structured interviews with managers included 57 questions and all the data collected were transcribed onto an Excel sheet for comparison and further analysis as suggested by Flick (2014). The most relevant data for understanding the management of wastewater treatment was used to build up a body of knowledge for the studies. In addition to the interviews with managers, semi-structured interviews were also conducted with other stakeholders. Table 3-4 details the number of semi-structured interviews conducted for this thesis. Semi-structured interviews with users (e.g. families, schools, and health centres) were conducted to collect information on their perception of the service, aesthetic issues, willingness to pay a higher tariff, and other information that was useful to help understand the context. Farmers were interviewed in their role as the beneficiaries of the treated wastewater as part of a concerted effort to collect information on wastewater irrigation practices (e.g. types of crops, reuse seasons, etc.), benefits, and risks. The structure of the interviews with managers is presented in Paper II under Supplementary material, and with households, institutions and farmers in Appendix A.

Table 3-4. Details of semi-structured interviews conducted for the development of the thesis.

Case studies	Managers/Board members	No. of families	No. of farmers	No. of schools	No. of health centres	Total
CS1	1	23	-	3	-	**27**
CS2	1	21	6	3	1	**32**
CS3	1	22	4	5	1	**33**
CS4	1	12	5	1	1	**20**
CS5	1	10	3	-	-	**14**
CS6	1	11	-	-	-	**12**
CS7	1	-	-	-	-	**1**
CS8	1	-	7	-	-	**8**
CS9	1	-	3	-	-	**4**
					TOTAL	**151**

3.3.3 Literature review

A systematic literature review was made using the Scopus database to identify standard sustainability indicators applied at wastewater treatment plants. The search included studies implemented since 2000, and the key words were ‘sustainability’, ‘criteria’, ‘indicator’ and ‘wastewater treatment plants’, and combinations thereof. Relevant studies were selected according to content relating to sustainability indicators for the assessment of WWTPs. The studies selected were categorized according to the World Bank Country Income Classification list, i.e. high, upper-middle, lower-middle, and low income (World Bank, 2018) in relation to the country in which the study was conducted. In addition, the phase in which the sustainability assessment was made in each study was considered for categorization purposes, i.e. planning phase or operational phase. All the sustainability indicators identified in the selected studies were clustered according to similarities and the dimension to which it was related in the literature. The systematization of the indicators resulted in a comprehensive list of sustainability indicators to assess wastewater treatment plants in the planning and/or operational phase. Indicators mentioned in one-third or more, i.e. $\geq 33\%$, of the selected studies, were identified and considered to be standard indicators.

3.3.4 Focus groups – SWOT analysis

Focus groups with local stakeholders were used to contextualise the theoretical indicators identified in the literature review. The focus group meetings were run with members of the water association boards and WWTP managers/operators from each of the five case studies included at this stage (CS1 – CS5). Five to seven members participated in each of the five focus groups. Discussions in focus groups are useful as a means of gathering complementary data that are not easily available through individual interviews with participants (Flick, 2014). They also promote better qualitative data collection as interaction between participants inherently validates the information (Flick, 2014). They also promote better qualitative data collection as interaction between participants inherently validates the information (Flick, 2014). The discussions in each focus group were based on the performance assessment results that were presented for each WWTP in Paper I (Cossio et al., 2017b). The purpose was to motivate a SWOT (Strength, Weakness, Opportunity and Threat) analysis of the management practices at each WWTP. When a lack of systematized information regarding a system is a limitation, looking back on its management history can support the identification of critical aspects in its assessment and future improvement (Cuppens et al., 2013). Leading questions for the brainstorming ideas were: What is working well? What are the main issues in the sewage service? What are the main issues at the WWTPs? What is causing the problems? How can these problems be solved? What do we do first? How can these improvements be measured? The information was set out on a flipchart in front of the participants until the data collection was saturated. The information from the eight focus group exercises was then transcribed according to their similarities under strengths, weaknesses, opportunities and threats.

3.3.5 Workshops

The aim of the workshops was to formulate local sustainability indicators in order to finalize the contextualization of the theoretical indicators identified in the literature review. Workshops were organized with local experts who had worked on the water and sanitation projects in Bolivia. In a Bolivian context these types of projects have two main components: technical and social. Consequently, local experts within these two fields were invited to participate in two separate workshops. There were seven participants from the technical field and six from the social field. The formulation of indicators was based on previous findings in Paper I (Cossio et al., 2017b) and the results from the SWOT analysis with managers that were presented to the local experts. The participants were instructed to identify any additional aspect that could be missing in relation to the SWOT analysis. They were then asked to formulate local indicators in relation to all critical aspects that could affect the sustainability of the WWTPs, and rank the sustainability dimensions according to their relevance to the local context. Local experts wrote their input on post-it notes, which were then arranged on a whiteboard under each of the sustainability dimensions to permit further ranking and systematization. A ranking was also done during the workshop, with a request that the participants in each workshop assign a value to the five dimensions, ranging from 1 for most important to 5 for least important.

3.3.6 Validation and testing

The validation process aims to reduce misrepresentations of the findings or results when developing qualitative research (Stake, 1995; Yin, 2016). The validation was made together with the stakeholders to obtain feedback and reduce misinterpretation through their points of view on the findings of the studies. This was done when presenting the WWTP performance results (Paper I) to local stakeholders for further analysis and discussion (i.e. for the purpose of the focus group meetings and workshops).

The sustainability assessment tool was tested in two case studies (CS8 – CS9). The aim was to receive feedback on the practicality of the tool by performing assessments of the two WWTSs together with assessors. The researcher guided the testing of the tool and noted all the comments and suggestions provided regarding improvements in data collection or questions difficult to assess in the tool. Some of the suggestions provided were used to update the tool, whereas other suggestions were kept as a part of potential improvements of the tool.

3.3.7 Limitations in the data collection

Composite sampling was not possible due to limitations, such as a long distance to the field site or physical conditions at the sampling points, which were not easy to access at certain times due to lack of maintenance or heavy rain. Lack of records and systematized information from stakeholders regarding the management of the WWTPs in the case studies was a further limitation during the field studies. Limited time did not allow to test the tool with all case studies or other stakeholders included in the thesis.

3.4 Assessment methods

3.4.1 Performance assessment

The performance assessment of WWTPs was implemented by adapting the framework suggested by the International Water Association (IWA) (Matos et al., 2003; Balmér and Hellström, 2012). This method was used to assess performance in five case studies, Paper I (CS1 – CS5). The performance was assessed with regard to: i) treatment efficiency for total suspended solids (TSS), biochemical oxygen demand (BOD), and log unit removal of faecal coliforms (FC); ii) the effluent quality with concentrations of pollutants for TSS, BOD, chemical oxygen demand (COD), and FC (Matos et al., 2003; Balmér and Hellström, 2012); and iii) operational parameters, such as hydraulic retention time (HRT), hydraulic loading rate (HLR), and organic volumetric load (OVL). These operational parameters were used to assess the actual treatment capacity compared with the envisaged capacity when it was designed.

3.4.2 Quantitative microbial risk assessment

Wastewater irrigation was identified as a common practice in the case studies included in this thesis. A Quantitative Microbial Risk Assessment (QMRA) was made to estimate human health and ecological risks associated with this practice using different scenarios in five case studies in Paper II (CS3 – CS4 and CS7 – CS9). Quantitative microbial risk assessment estimates the risk to human health arising from exposure to infectious microorganisms in specific scenarios (Haas et al., 2014). The risk estimation was performed using Monte Carlo simulations in Excel and the input data includes pathogen concentration, exposure pathways, and pathogen infectivity. Human health risks associated with lettuce consumption irrigated with wastewater in three scenarios (i.e. raw wastewater, actual effluent, and expected effluent) were estimated for enterovirus, *Salmonella* spp and *Ascaris lumbricoides*. Ecological risks were estimated for accumulation of nitrogen and phosphorus in the soil for lettuce and maize crops.

3.4.3 Traffic light method

The traffic light method was used to make a simplified assessment that could be used by local stakeholders. Variants of the traffic light method was applied in the management assessment of WWTPs in Paper II (CS3 – CS4 and CS7 – CS9) and in the development of the sustainability assessment tool in Paper IV. The traffic light method assesses the status of the system in an analysis using a scale with levels from not fulfilling a desired target at all to a level of fulfilling the target completely. Variables are coded using colours e.g. red for failure, yellow for off-track, green for fulfilled (Benavides et al., 2019; Brinkmann and Garren, 2018; Silva et al., 2014; Vatten, 2018). The colour-coded scales can be defined by using standard benchmarks. However, these benchmarks are not always available for certain indicators, especially those that measure qualitative aspects (e.g. awareness, public participation, customer satisfaction, etc.). It could also be the case that there is no available information on the status of the system in order to assess it using standard benchmarks. This lack of data and information is a common issue in low and lower-middle income countries. The scales for the assessment should therefore preferably be developed based on available information or information that can be easily collected. The advantage of applying this method is that it is simple and can be adapted easily by local stakeholders. However, the disadvantage is that scales, scores and interpretation of results could be subjective. Subjectivity in the assessment scales should thus be reduced to the lowest level possible in order to obtain reliable results (Benavides et al., 2019; Reed et al., 2006). Finally, these scales should be revised over time to ensure they correspond to the actual conditions in the system when analysed.

Management assessment of the WWTPs

In Paper II, the management of the WWTPs was assessed in order to relate the results to the existing human health and ecological risks from reusing wastewater treated at these facilities. The management assessment of the WWTPs was based on three criteria: i) the current performance regarding TSS and BOD discharge requirements, ii) the technological potential to reach health-based targets for pathogens and helminth egg reduction, and iii) operation and maintenance. The scales were set from 0 to 2 and colour-coded as follows: Red – 0 for non-fulfilment of the requirements, Yellow – 1 partial fulfilment of the requirements, and Green – 2 for fulfilment of all the requirements. The final score obtained for each criterion was normalized to a scale from 0 to 1, dividing the total score by the maximum score for that criterion.

Sustainability assessment tool

The development of the sustainability assessment tool in Paper IV included the traffic light method to provide local stakeholders with a method that could be easily applied and adapted to their specific requirements. In the scale defined for the sustainability assessment tool presented in this thesis, five levels from 0 to 4 were colour-coded and assigned the scoring system shown in Table 3-5.

Table 3-5. Scales with colour-coded scores and descriptions defined for the sustainability assessment tool for wastewater treatment in Bolivia or other low and lower-middle income countries.

Colour	Score	Description
Grey	0	No information available/Not applicable
Red	1	Requirement/Optimal level not fulfilled
Yellow	2	Requirement/Optimal level partly fulfilled
Light green	3	Requirement/Optimal level fulfilled relatively well
Dark green	4	Requirement/Optimal level fulfilled

4 RESULTS

This chapter includes the results of the four papers that are appended and a smaller study on user perception of the WWTSs. The development of the EVAS tool for sustainability assessment of the WWTSs using contextualized indicators for small WWTSs in Bolivia is also presented.

4.1 Paper I – Performance assessment

The assessment of the performance of five wastewater treatment plants (WWTPs) was based on wastewater analyses and interviews with managers: three WWTPs serving small towns (CS1 – CS3) and two WWTPs serving villages (CS4 – CS5). The wastewater characterization process revealed that CS3 had a high contaminant concentration (TSS and BOD) compared to the other four case studies. CS1, CS2, CS4 and CS5 thus revealed a low-medium contaminant concentration (Figures 4-1, A and B). The higher contaminant level in CS3 was possibly due to the fact that this town has a higher level of industrial activity compared to the towns and villages in the other case studies. As regards pathogen concentrations (i.e. FC), all five case studies (CS1 – CS5) consistently revealed medium-level concentrations (Figure 4-1, C). The operational parameters, such as hydraulic retention time (HRT), hydraulic loading rate (HLR), and organic volumetric load (OVL), generally showed that the WWTPs are functioning sub-optimally with a lower HRT than expected and a higher HLR and OVL. Among the technologies evaluated (i.e. Imhoff tanks, stabilization ponds, biofilter), the performance level of the Imhoff tanks was the lowest. This could possibly be attributed to a lack of regular desludging of the digestion chamber. In addition, in two of the WWTPs (CS2 and CS4), there was no pre-treatment prior to the Imhoff tanks, which led to more frequent maintenance due to accumulation of solids in the tank. The absence of a pre-treatment unit could result in the subsequent process units at a WWTP performing inadequately. CS3 had the highest level of removal efficiency among all the treatment plants evaluated, probably due to the fact that it included an adequate pre-treatment unit and two treatment trains in parallel up to the tertiary level (i.e. maturation ponds). None of the WWTPs in the case studies, including CS3, achieved the removal rates expected for these technologies under normal operating conditions. The results are presented in Table 4-1. Moreover, the national discharge limits for TSS, BOD and COD (i.e. 60 mg/L, 80 mg/L and 250 mg/L) were not complied with at any of the WWTPs, except for COD in the case of CS3 and CS5.

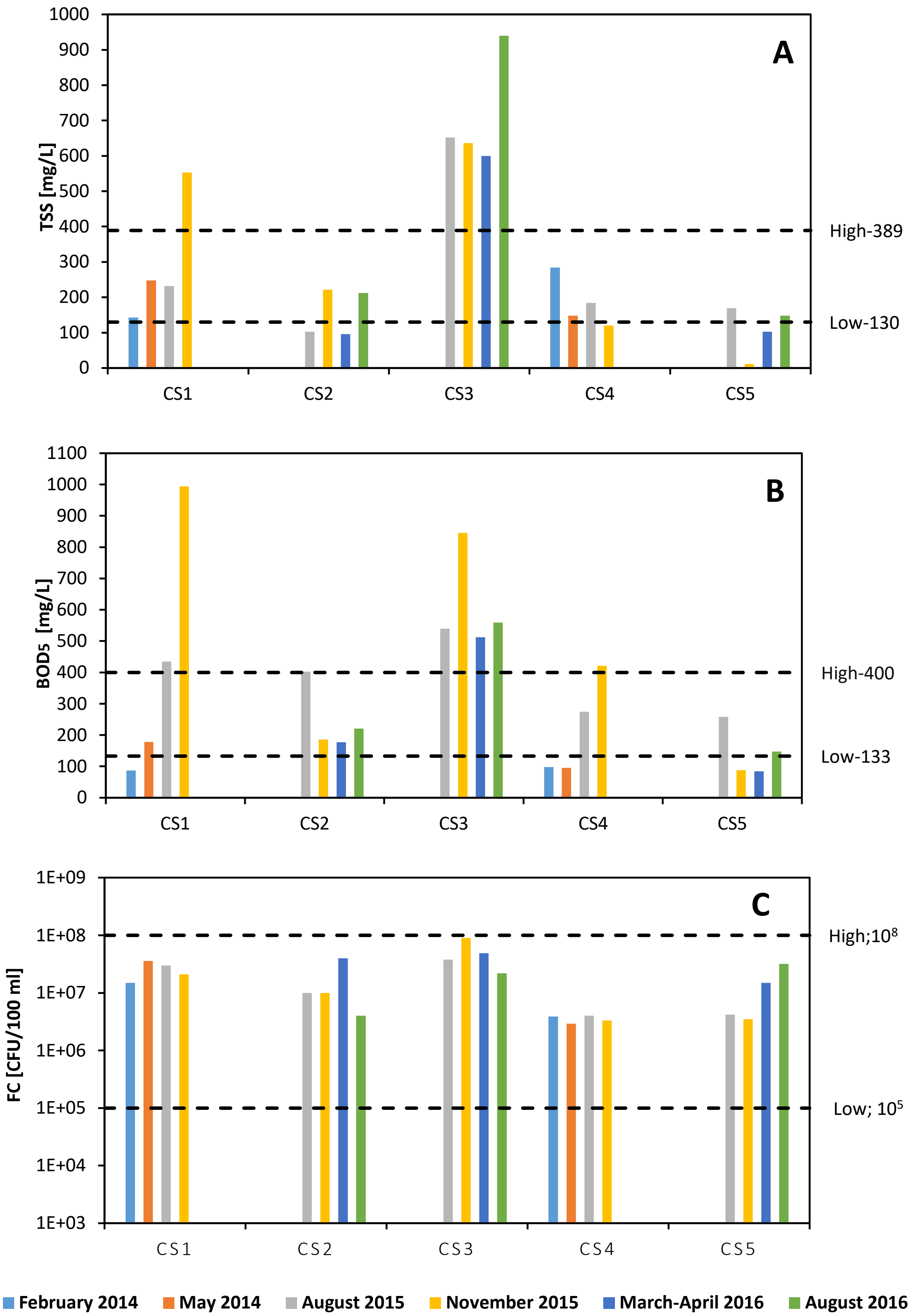

Figure 4-1. Concentrations of TSS (A), BOD (B), and FC (C) in the influent of the five wastewater treatment plants monitored. The coloured bars represent the months during which the sampling campaigns were conducted.

Table 4-1. Average removal efficiency levels of the WWTPs in CS1 – CS5 and expected removal efficiency levels for each type of technology.

Case study	Level of treatment	TSS %	BOD_5 %	FC Log units
CS1	Pre-treatment + Primary treatment (1 Imhoff tank) + Secondary treatment (1 Anaerobic filter)	31	17	0
CS2	Primary treatment (2 Imhoff tanks)	14	3	0
CS3	Pre-treatment + Primary treatment (2 Anaerobic ponds)	86	70	0.9
	Secondary treatment (2 Facultative ponds)	12	13	0.8
	Tertiary treatment (4 Maturation ponds)	40	14	0
CS4	Primary treatment (Imhoff tank)	66	19	0
CS5	Pre-treatment + Primary treatment (2 Imhoff tanks)	27	12	0.4
Expected removal efficiency levels[1]	*Imhoff tank*	*40 - 50*	*25 - 35*	*NA*
	Anaerobic filter	*50 - 80*	*50 - 80*	*1-2*
	Anaerobic pond	*NA*	*50 - 80*	*NA*
	Facultative pond	*90*	*75 - 95*	*2-3*
	Maturation pond	*20 - 30*	*20 - 50*	*3-4*

[1] Massoud et al., 2009

The interviews with the managers helped to identify the main potential reasons for low performance levels at the WWTPs. There were shortcomings in operation and maintenance, either due to lack of funding to hire staff, or a lack of technical expertise to assist in carrying out complex maintenance tasks. Design issues were another reason for not being able to carry out adequate maintenance, e.g. deep grit chambers that were not easy to access, and screens that formed part of the inlet of the Imhoff tank instead of operating separately as part of a preceding unit. Further design issues were related to Imhoff tanks that were reported to be difficult to maintain as desludging would require specific technical expertise and special equipment to sustain the frequency required for optimal performance.

Other issues were related to the functionality of the sewer network, which was affected by inadequate installations in households and at industrial facilities. There was no regular monitoring system in place in any of the case studies to evaluate the performance of the WWTPs, and managers did not have any flow or wastewater analysis records covering the period before the studies included in this thesis commenced.

Management of the very small WWTPs in the villages follows a community-based organization model. In this model, the villagers are directly involved in activities related to the development of their community, generally overseen by a group of leaders. In the two case studies in which this management model was employed, i.e. CS4 and CS5, users were involved in the maintenance of the WWTPs when required.

4.2 User perception of the WWTS

This section presents some of the results obtained from the semi-structured interviews with users, which are not included specifically in the four papers presented in this thesis. However, the study has contributed to acquiring a better understanding of the context and the process of building up knowledge of the systems studied in this thesis.

Users from households, schools and health centres were interviewed in CS1 – CS6. A summary of the main results from the interviews is presented in Figure 4-2 and includes answers to the following questions: *Is the sewer network working efficiently? Is the sewer network connected to a WWTP? Do you have information about the WWTP? Do you know where the effluent of the WWTP is discharged?* In the small towns and villages that were studied, the WWTPs were not far from the users' homes, as the network was based on a gravity sewer system.

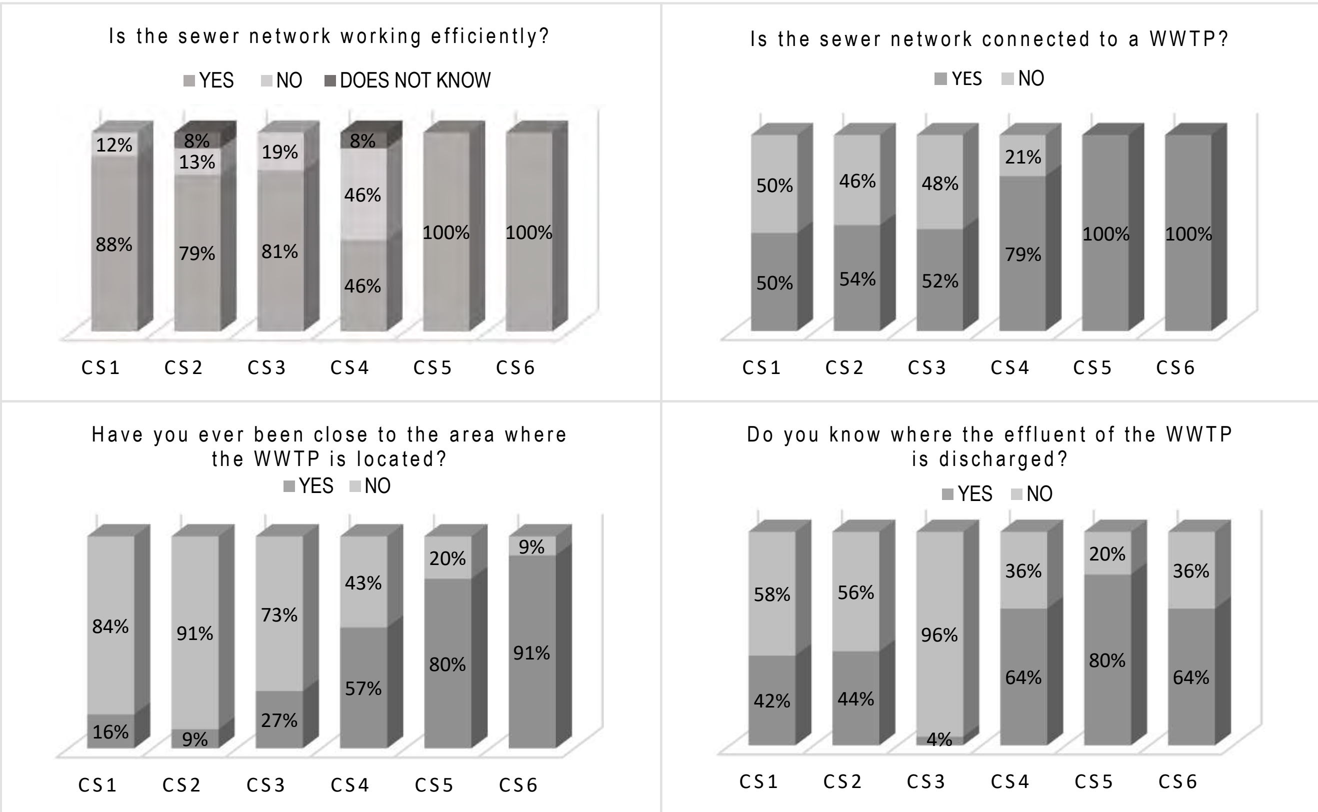

Figure 4-2. Summary of the main results from semi-structured interviews with users in CS1 – CS6. The bar graphs show the percentage of answers given by the interviewees.

Is the sewer network working efficiently?
In small towns (CS1 – CS3), a low percentage of the respondents answered *No* to this question, indicating that from their point of view there were no significant problems with the sewer network. In CS5 and CS6, 100% of the users replied that the sewer network was working efficiently. In the case of CS5, the users themselves were responsible for

carrying out monthly maintenance. In CS6, only 10% of the users for which the system was designed were connected to the system (8 out of 80). In this case study, three interviews were conducted with families who were not connected, the aim being to understand the reasons for the low connection rate in this particular village. They reported that there was no need to connect because they were using a toilet with a pit latrine or infiltration pit. As each user was personally responsible for connecting to the sewer network, they needed to know the exact location of the network, and they did not have access to that information. In CS4, 46% of the users responded *Yes* to this question and 46% *No*. In CS4, families that lived upstream did not use this service properly as they threw everything into the sewer network. Consequently, users downstream, close to the WWTP, had constant overflows due to blockages in the pipes, and they were responsible for maintaining the pipes to solve the problem. There was a lack of awareness of this among users upstream as they did not have any such issues.

Is the sewer network connected to a WWTP?
Respondents in small towns (CS1 – CS3) stated that only 50% of the users knew about the existence of a WWTP. In CS4, 21% said *No* and in CS5 – CS6, 100% knew about the WWTP. For CS5, the reason may be that it was the users themselves who carried out the maintenance every month and for CS6 it is most likely to be a result of the fact that the WWTP was located close to where they lived.

Do you have information about the WWTP?
In CS1 – CS3, the answer to this question was predominantly *No,* since users were not involved in the operation and maintenance of the WWTPs. They pay the tariffs and expect the board and the management staff who had been hired to take responsibility for the service and ensure it is operating properly. This is in contrast to CS5, where users were responsible for these tasks and thus had a greater sense of responsibility. The responses for CS4 were 57% *Yes* and 43% *No.* It was mostly users that lived close to the WWTP who replied *Yes.* They were aware of the existence of the WWTP as they were affected more directly by the smell from the plant. Further questions were put to users who replied in the affirmative (*Yes*) to this question. They were asked questions regarding the functionality and aesthetics of the WWTP, see Figure 4-3 and the corresponding text.

Do you know where the effluent of the WWTP is discharged?
Answers to this question were similar in CS1 and CS2 with less than half of the respondents knowing the location of the discharge point (see Figure 4-2). In both cases the discharge was into streams close to the WWTP. In CS3, 96% of users did not know where the point of discharge was, and in this case study a farmer actually reused all the treated wastewater. In CS4 – CS6 most of the users knew that treated wastewater was discharged into streams close to the WWTP as most of the users also lived close to the WWTP.

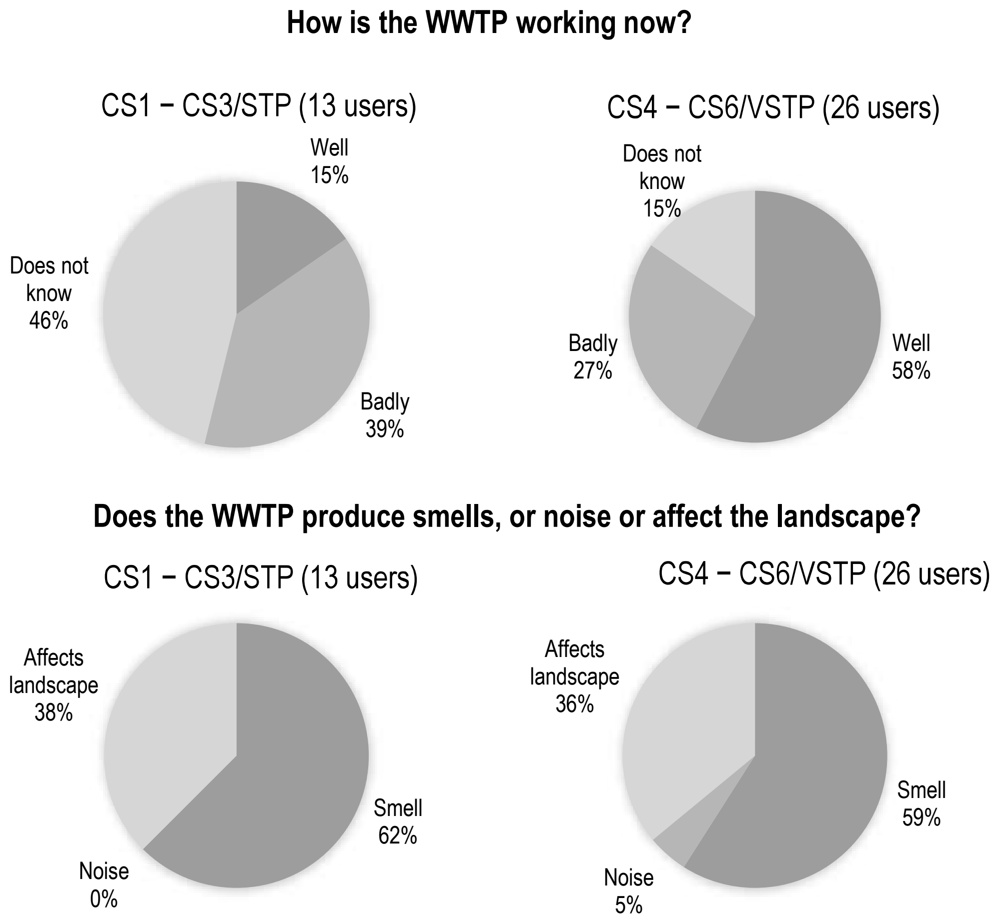

Figure 4-3. Summary of the main results from semi-structured interviews with users regarding the functionality and aesthetics of the WWTPs for CS1 – CS3/STP (13 users interviewed about STP - small treatment plants) and CS4 – CS6/VSTP (26 users interviewed about VSTP - very small treatment plants).

How is the WWTP working now?
The majority of respondents in small towns did not know how the WWTP was working (46%) or that the WWTP was working badly (39%). This is in contrast to the villages, in which 58% answered that the WWTP was working well, even though this assessment was based more on the fact they had not had any blockages or overflows rather than actual knowledge of how well the treatment plant was working.

Does the WWTP produce smells or noise or affect the landscape?
Answers regarding aesthetics in relation to the functionality of the WWTP were similar in both groups interviewed (i.e. small towns and villages). Smells originating from the WWTP were the main issue for 62% and 59% of respondents from small towns and villages, respectively. The second most pressing issue was related to negative impact on the landscape, which was highlighted by over a third of the respondents in both cases.

Noise pollution was not reported as an issue as there were no mechanical components included in the technologies used in these WWTPs.

One of the main findings of the user perception study was that in general users in the villages are more aware and are more knowledgeable with regard to the WWTS compared to users in the small towns. However, in CS4 the users from the villages behaved differently and had a different perception of the service depending on where they lived in the village (i.e. in the upper section of the network or in the section close to the WWTP). Nevertheless, the village in CS4 generally had a greater degree of awareness, sense of ownership, and feeling of responsibility for ensuring the service was working well compared to the small towns. The low connection rate in CS6 shows that there was no real demand from the population to introduce a wastewater treatment system.

In small towns, the users were able to say how the sewer network was working, although awareness of the existence of the WWTP was low. This indicates that the managers or board members of the organizations in charge of wastewater treatment did not inform users about the wastewater treatment services.

4.3 Paper II – Human health and ecological risks

This study investigated how the management of the WWTPs in five case studies impacted on human health and ecological risks when three different water sources are used for irrigation: raw wastewater, actual effluent with the current level of treatment, and expected effluent if the treatment system performed optimally. The potential risks were estimated and compared for the three scenarios. Estimates were made of human health risks associated with lettuce consumption and ecological risks associated with accumulation of nutrients (i.e. nitrogen and phosphorus) when irrigating lettuce and maize. This was done in conjunction with an assessment of the management of the WWTPs, which made it possible to analyse the impact of the management of the WWTPs on the above risks.

In this study five case studies were used: CS3, CS4, CS6, CS7, CS8. The results from the management assessment of the WWTPs in the cases studied are presented in Table 4-1. The management assessment measured i) the current performance of the WWTPs, ii) the technological potential of the WWTPs to remove pathogens, and iii) how operation and maintenance were carried out. The results showed that the highest mean normalized score was obtained by CS8 with 0.55, followed by CS3 and CS7 with 0.42 and 0.33 respectively, all on a scale of 0-1. In CS8, a normalized score of 0.9 for Criterion 3 - Operation and maintenance contributed significantly to its overall score, indicating that the majority of the requirements for optimal operation and maintenance were fulfilled. This contrasts with the result for CS3, where the requirements for optimal operation and maintenance were not fulfilled at all, thus scoring 0 for Criterion 3 - Operation and maintenance. In the case of Criterion 2 - Technological potential, CS3 scored 0.75 compared to 0.25 for CS8.

Table 4-1. Results from the assessment of the management of the WWTPs in CS3 – CS4 and CS7 – CS9. Scale for individual scores: 0/non-functional to 2/performing well, and normalized scores: 0-1 (optimal performance).

No.	Indicators	CS3	CS4	CS7	CS8	CS9
	Criterion 1 - Current performance					
1	Meets national BOD discharge requirements	1	0	0	0	0
2	Meets national TSS discharge requirements	1	0	1	2	0
	Normalized score for Criterion 1	**0.50**	**0.00**	**0.25**	**0.50**	**0.00**
	Criterion 2 - Technological potential					
3	Potential to reach the health-based target of 6 $\log_{10}$ pathogen reduction for unrestricted irrigation.	1	0	0	0	0
4	Potential to reach the health-based target of ≤1 helminth egg per litre in the effluent used for unrestricted irrigation.	2	0	1	1	0
	Normalized score for Criterion 2	**0.75**	**0.00**	**0.25**	**0.25**	**0.00**
	Criterion 3 - Operation and maintenance					
5	Meets the required level and availability of technical expertise needed for optimal O&M (technology-specific).	0	0	1	2	0
6	Performs the required O&M activities and provides the required pre-treatment frequency (technology-specific).	0	0	1	2	0
7	Performs the required O&M activities at the main process units (technology-specific).	0	0	1	2	0
8	Performs the required long-term maintenance activities in the main process units (technology-specific).	0	0	2	2	0
9	Has the required monitoring system in place to ensure optimal O&M (technology-specific).	0	0	0	1	0
	Normalized score for Criterion 3	**0.00**	**0.00**	**0.50**	**0.90**	**0.00**
	Mean normalized score	**0.42**	**0.00**	**0.33**	**0.55**	**0.00**

The risks estimated for enterovirus showed that the probability of exceeding the maximum additional disease burden of 10^{-4} DALYs person^{-1} year^{-1} in developing countries was higher between 25 and 2.5% in CS8 for the raw wastewater and the theoretical effluent scenarios, and between 50% and 25% in CS4 for the actual effluent scenario (see Figure 4-4). The results relating to exceeding the pre-existing disease burden of 10^{-2} DALYs person^{-1} year^{-1} reported in Bolivia indicated that the probability was low, slightly higher than 2.5%, of the actual effluent scenario in CS4 to exceed this threshold (see Figure 4-4). The results for CS8 indicate that fulfilling the operation and maintenance requirements for optimal performance of the WWTP could have probably reduced the estimated risks of the actual effluent compared with the expected effluent.

The disease burden of 10^{-4} DALYs $person^{-1}$ $year^{-1}$ was exceeded for *Salmonella* spp. with at least 75% probability for all scenarios in CS9 and for raw wastewater and actual effluent in CS3, CS4, CS7 and CS8 (see Figure 4-4). As regards the disease burden of 10^{-2} DALYs $person^{-1}$ $year^{-1}$ for Bolivia, the raw wastewater scenarios for CS3, CS7, CS8, and CS9 exceeded this threshold with at least 25% probability (see Figure 4-4). The results suggest that if health risks for *Salmonella* spp. are to be reduced to acceptable levels, improving operating and maintenance practices is not sufficient and upgrading of technologies would also be required.

The risks estimated for *A. lumbricoides* showed that the probability of exceeding the disease burden of 10^{-4} DALYs $person^{-1}$ $year^{-1}$ was 100% for the raw wastewater scenarios, and at least 75% for the actual effluent scenarios for CS3, CS4, and CS8. For CS7 and CS9, only the raw wastewater scenario exceeded this threshold with a probability of 100% and 75%, respectively (see Figure 4-4). The estimated risk for the scenarios with expected effluents and actual effluents for CS7 and CS9 were below the disease burden of 10^{-4} DALYs $person^{-1}$ $year^{-1}$ (see Figure 4-4). None of the fifteen scenarios revealed a risk for a disease burden higher than the pre-existing disease burden of 10^{-3} DALYs $person^{-1}$ $year^{-1}$ for Bolivia with regard to *A. lumbricoides* (see Figure 4-4).

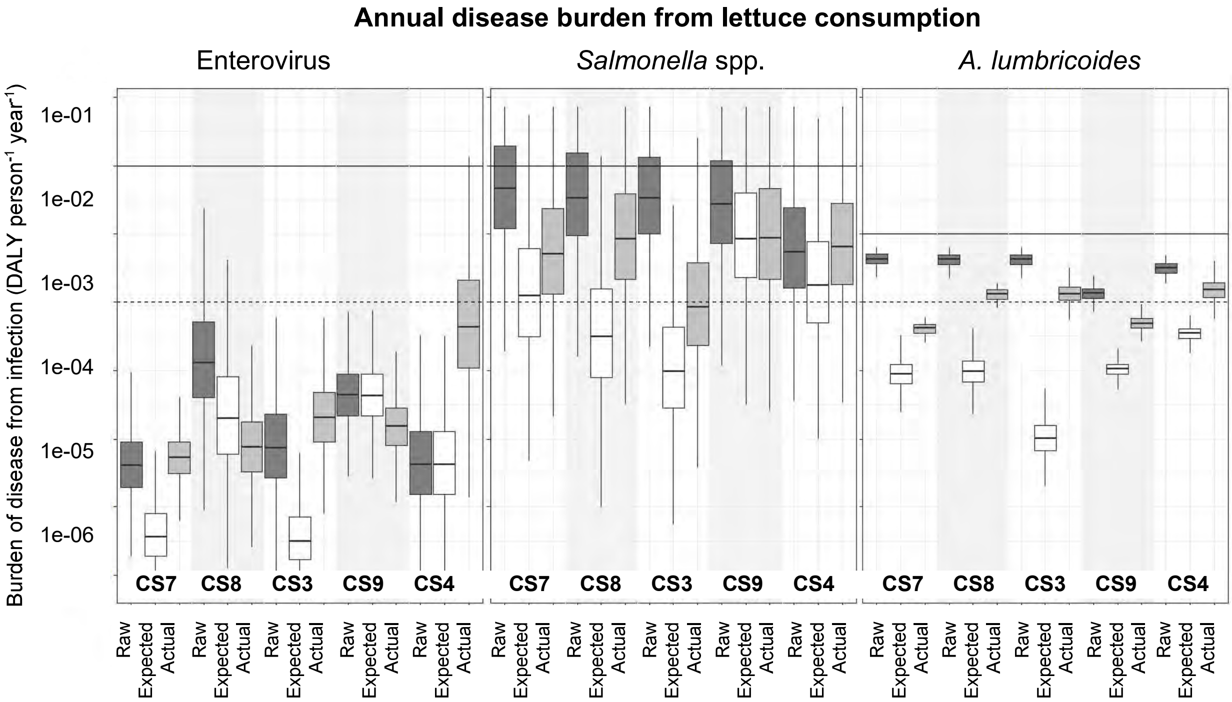

Figure 4-4. Disease burden estimated for Enterovirus, Salmonella spp. and A. lumbricoides from lettuce consumption associated to wastewater irrigation (i.e. raw-dark grey boxes, actual effluent-light grey boxes and expected effluents-white boxes) for Case studies 3-4 and 7-9. The lower, medium and upper lines in boxes represent the 25th, 50th and 75th percentile, respectively, and the whiskers represent the 95% credibility interval. The dotted line indicates the maximum additional disease burden allowed for wastewater reuse in low-middle income countries. The solid lines represent the disease burdens from diarrhoeal diseases (for Enterovirus and Salmonella spp.) and intestinal nematodes (for Ascaris lumbricoides) reported for Bolivia (Pruss-Ustun et al., 2008).

The risks estimated for nitrogen accumulation in soil (i.e. 100 – 200 kg N ha^{-1}) with actual effluent was higher than with expected effluent in all cases except CS5 (see Figure 4-5). As regards phosphorus accumulation in soil, the estimated risk was higher using actual effluent than the theoretical effluent for all the cases except CS3 for maize (see Figure 4-6). The probability of accumulation of nitrogen and phosphorus is higher for lettuce than for maize. Ecological risks in the soil regarding nitrogen and phosphorus accumulation could in theory be reduced if the theoretical effluent levels are reached. Despite this reduction in risk, further unit processes are needed to reduce the level of nitrogen and phosphorus to a safe level (95% probability of no excess), in order to avoid eutrophication of groundwater or surface water resources.

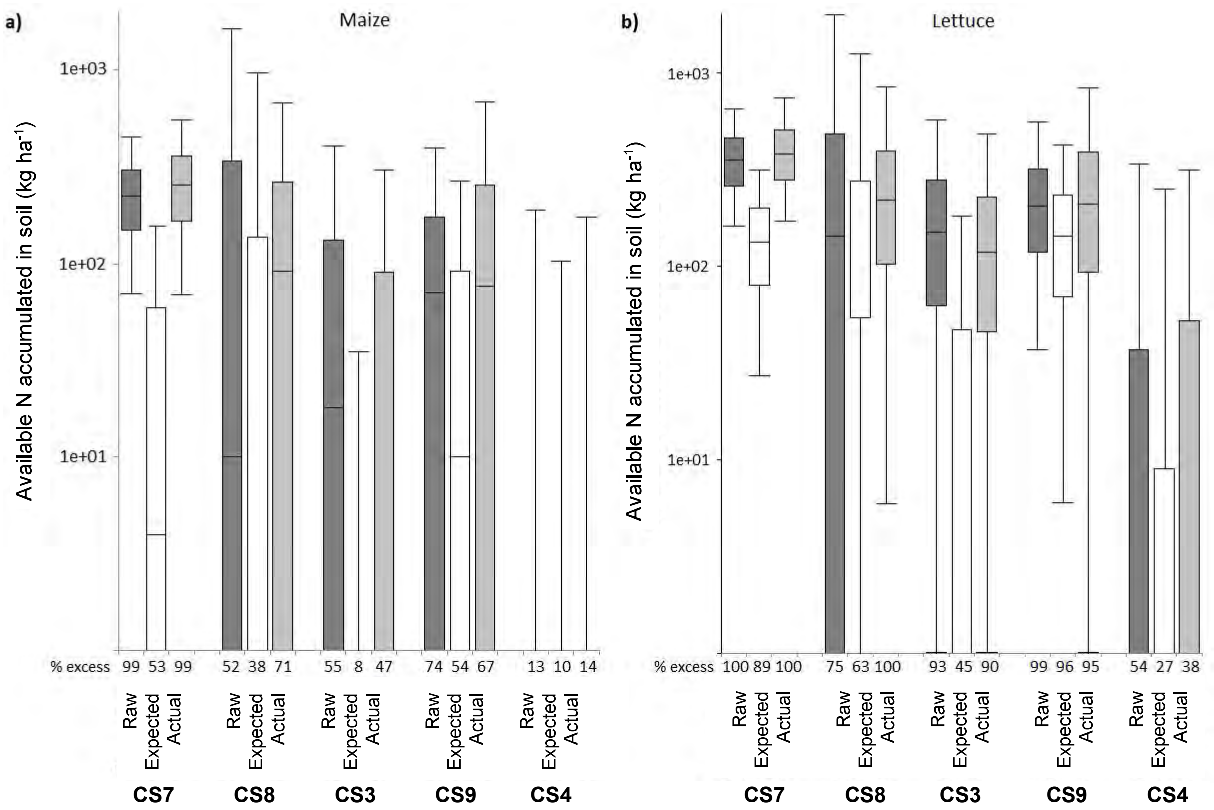

Figure 4-5. Simulated concentrations of available nitrogen (N) in soils irrigated with raw influent (dark grey boxes), actual effluent (light grey boxes) and theoretical effluent (white boxes) from the five small WWTPs studied (CS3, CS4, CS7, CS8, CS9) after one season of cultivation of (a) maize and (b) lettuce. The medium and upper lines in boxes represent the 50th and 75th percentile, respectively; and the lines above the boxes represent the 95% credibility interval. The numbers below the horizontal axis indicate the percentage of simulations resulting in positive values (excess N in soil).

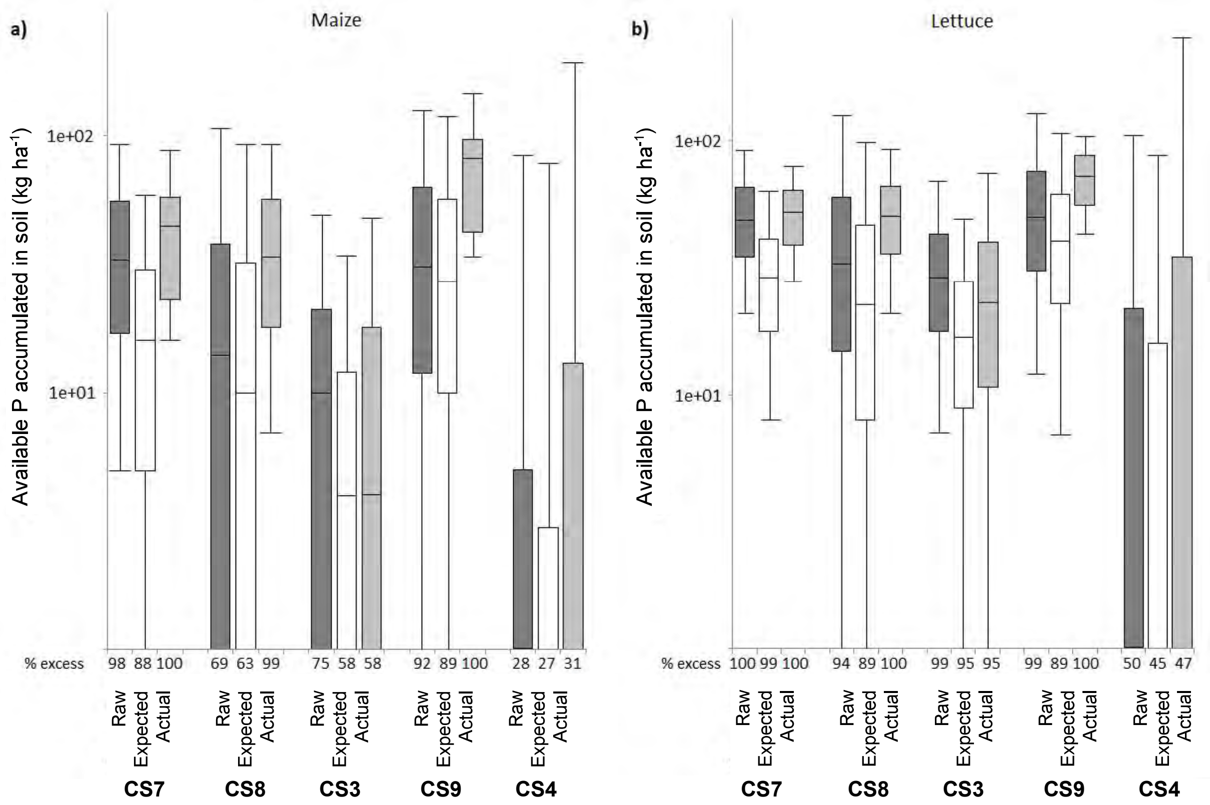

Figure 4-6. Simulated concentrations of available phosphorus (P) in soils irrigated with raw influent (dark grey boxes), actual effluent (light grey boxes) and theoretical effluent (white boxes) from the five small WWTPs studied (CS3, CS4, CS7, CS8, CS9) after one season of cultivation of (a) maize and (b) lettuce. The lower, medium and upper lines in boxes represent the 25th, 50th and 75th percentile, respectively, and the lines above the boxes represent the 95% credibility interval. The numbers below the horizontal axis indicate the percentage of simulations resulting in positive values (excess P in soil).

4.4 Paper III – Sustainability indicators

This study aimed to identify sustainability indicators for the assessment of WWTPs in the context of low and lower-middle income countries. The systematic literature search found 43 studies for inclusion in the systematization of sustainability indicators, with only four studies carried out in lower-middle income countries and none carried out in a low income country. The review of the 43 studies identified 40 unique sustainability indicators for the assessment of WWTPs. From the list of 40 indicators, 12 standard sustainability indicators (Table 4-2) were selected as they were mentioned in 33% or more of the studies selected. The dimensions in which these 12 standard indicators were included were: Environmental, Social, Economic, and Technical.

Table 4-2. Standard sustainability indicators for the assessment of WWTPs, organized into the dimensions in which they were included in the studies (i.e. Environmental, Social, Economic, and Technical).

Dim.	Indicator	Description
Environmental	Energy use	Energy used per volume unit of treated wastewater or inhabitant.
	Global warming potential	Emissions of greenhouse gases (GHG) into the atmosphere.
	Removal of BOD, TSS, TN, TP, and FC	Contaminant removal efficiency to mitigate health and environmental risks.
	Land area	Land area required for the wastewater treatment facility.
	Quality of effluent and sludge	Pollutants discharged into water and toxic compounds discharged into soil.
	Potential recycling	Reuse of treated wastewater: nutrients (N, P) and energy.
Social	Public acceptance	Opinion of the local population affected by the plant.
	Aesthetics	Measured level of nuisance deriving from e.g. smell, noise, visual impact, insects, and other pests.
Economic	Investment costs	Cost of construction and installation of the WWTP.
	Operating and maintenance costs	Operating costs per volume unit of wastewater treated.
Technical	Reliability	Infrastructure or mechanical reliability; resilience; security; ability to endure shock loads and/or seasonal effects; potential for overflow.
	Complexity of construction and O&M	Ease of construction, complexity of plant construction and system installation; complexity of operation and maintenance; professional skills required for operation and maintenance.

p.e. = population equivalent which expresses the ratio between the sum of the pollution load produced during a 24-hour period by institutions (i.e. schools or health centres) and the individual load produced by one person in a household.

To assist in the identification of locally relevant sustainability indicators, a SWOT analysis was performed with managers at local WWTPs. During the participatory SWOT analysis, the managers had in-depth discussions about the underlying causes of the low performance of the WWTPs and their management issues (e.g. low tariffs, lack of operation and maintenance). The results from the SWOT analysis (i.e. Strengths, Weaknesses, Opportunities, and Threats) are set out in Figure 4-7.

S	W
▪ Participation of users ▪ Good leadership and commitment ▪ Regulations and statutes in place for management of the WWTP ▪ Board members train the users ▪ Timely payment of tariffs	▪ Issues with the sewer network ▪ Lack of awareness of adequate use of the sewer network ▪ Lack of information from managers regarding the sewer network ▪ Tariffs collected are insufficient ▪ Lack of technical capability ▪ Lack of monitoring at the WWTPs. ▪ Unclear regulations for connection to the sewer network ▪ Lack of institutional capacity to manage the WWTPs ▪ Unclear roles at higher institutional levels with regard to the management of the WWTPs
O	**T**
▪ Support from the local university ▪ Support from the municipality ▪ Public communication through local social media ▪ Support from users ▪ Support from international NGOs	▪ Public health issues ▪ Environmental risks ▪ Rain causes overflows in the sewer network and at the WWTP ▪ Irrational use of water due to a lack of water meters ▪ Wastewater from health centres without pre-treatment ▪ Lack of communication among local stakeholders

Figure 4-7. Results from the SWOT analysis (Strengths, Weakness, Opportunities, and Threats) identified by managers with regard to the management of the WWTPs in the case studies.

The contextualization of sustainability indicators together with local experts resulted in a list of 27 sustainability indicators applicable in the local context studied (Table 4-3).

Table 4-3. List of contextualized sustainability indicators. Indicators marked in bold type are standard sustainability indicators. Indicator marked in italic is the newly formulated local indicator. Suggested units for measurement. Local relevance of each indicator pointed out by managers or experts.

Dim.	Indicator	Suggested units	Local relevance	
			Managers	Experts
Environmental	**Energy use**	kW/p.e. kWh/m^3		
	Global warming potential	kg CO_2 eq./p.e.-year kg CO_2 eq./m^3		
	Removal of BOD, TSS, TN, TP, and FC	%	✓	✓
	Land area	m^2/p.e.		
	Quality of effluent and sludge	mg/L kg/p.e.-year	✓	✓
	Potential recycling	g/p.e.-year %		✓
	Eutrophication potential	kg of N, P/p.e.-year kg PO_4 eq./m^3		✓
Social	**Public acceptance**	Scoring system*		✓
	Aesthetics	Scoring system*		✓
	Public health risk	No. of outbreaks/unit population	✓	
	Participation	Scoring system*	✓	✓
	Staff requirements	No./flow rate	✓	✓
	Employee satisfaction	Scoring system*		✓
	Awareness	Scoring system*	✓	✓
	Expertise	No. of experts/skilled staff	✓	✓
Economic	**Investment costs**	$/p.e.-year $/$m^3$		
	Operating and maintenance costs	$/$m^3$		✓
	Tariff	$/month	✓	✓
	Cost effectiveness	Scoring system*	✓	✓
	Affordability	$/$m^3$ % of income/m^3	✓	✓
Technical	**Reliability**	Scoring system*		
	Complexity of construction and O&M	Scoring system*	✓	✓
	Sewer network functionality	*No. of failures/month*	✓	
Institutional	Interactions	No. of events/year	✓	✓
	Institutional capacity (water association)	Scoring system*	✓	✓
	Institutional capacity (higher level)	Scoring system*	✓	✓
	Information	Scoring system*	✓	

Within the 27 contextualized indicators, sewer network functionality was added as a new local indicator due to its importance to the functioning of the WWTP. Results showed that the sewer network must be included in the assessment of the whole WWTS. Standard indicators related to Energy use, Global warming potential, Land area, Investment costs, and Reliability were not mentioned in the workshops with local experts but were included in the list as they arise frequently in expert literature. The final list of 27 contextualized sustainability indicators thus includes 12 standard sustainability indicators, one new local indicator (i.e. sewer network functionality), and 14 additional indicators that were locally relevant and matched with sources from the literature review. The final set of contextualized sustainability indicators were included in five dimensions: Environmental, Economic, Social, Technical, and Institutional. A ranking of sustainability dimensions carried out by the two groups of local experts identified the Institutional dimension as the most important and the Environmental dimension as the least important (Table 4-4).

Table 4-4. Ranking of the dimensions by local experts according to their relevance to the sustainability of the WWTPs. The number in brackets indicates the prioritization level assigned by the group during the exercise. 1 = most important 5 = least important.

Field of expertise	Dimensions and ranking				
Technical field	Institutional (1)	Social (2)	Technical (3)	Economic (4)	Environmental (5)
Social field	Institutional (1)	Economic (2)	Social (3)	Technical (4)	Environmental (5)

This suggests that in the context of low and lower-middle income countries, institutional aspects are crucial to assure sustainable wastewater treatment services. The technical experts considered the Social dimension to be second in relevance, whereas experts from the social field ranked the Economic dimension as the second most relevant. The final contextualized dimensions are illustrated in Figure 4-8, from the core i.e. Institutional, Social, Economic, Technical and Environmental ranked according to local experts.

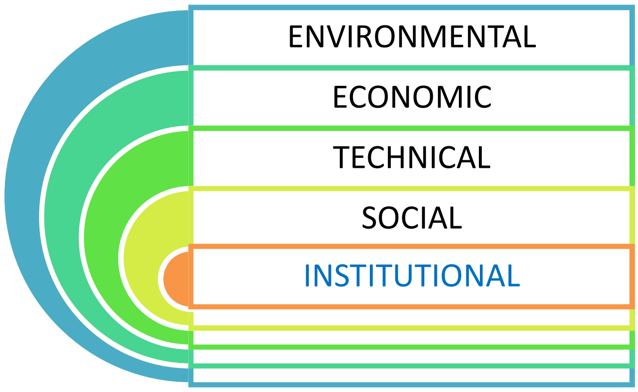

Figure 4-8. Illustration showing the dimensions proposed for sustainability assessment in Bolivia/low and lower-middle income countries and ranked by local experts (i.e. Institutional, Social, Technical, Economic and Environmental).

4.5 Paper IV – Sustainability assessment tool EVAS

A sustainability assessment tool named EVAS ("EVAluación de Sostenibilidad" or EVAluation of Sustainability) was developed using the findings from the previous studies in this thesis. The tool is based on a scoring system for sustainability dimensions, indicators, sub-indicators and factors to obtain an overall sustainability score for the WWTS. The scoring system applies the traffic light method with a scale from 0 to 4. Consisting of 0/grey-no information available, 1/red-requirement not fulfilled, 2/yellow-requirement partly fulfilled, 3/light green-requirement fulfilled relatively well and 4/dark green-requirement fulfilled. The tool includes 21 sustainability indicators within five sustainability dimensions, i.e. technical, environmental, social, economic, and institutional (Table 4-5). Each indicator and sub-indicator is scored based on different factors that describe in more detail the target levels for achieving a high level of sustainability. For instance, the factor T1-I. Monitoring to assess the Removal efficiency, assesses how frequently the constituents in the wastewater are monitored in the influent and effluent. The tool includes the weighting of dimensions, indicators, sub-indicators, and factors. The pre-set weightings used in this study are presented in Table 4-5. The tool design allows the assessor to change these weightings if different priorities are identified in the local context. The assessment provides a list of scores for all the factors, which can then be used by managers to prioritize improvement measures by identifying the factors that received lower scores (0, 1 or 2). The assessment results can also be used to communicate with local authorities about the actual status of the WWTS in order to prompt the formulation of strategies to improve the sustainability of the services.

Table. 4-5. Overview of the content of the sustainability assessment tool. List of sustainability dimensions, indicators, sub-indicators, and factors, and their respective weightings (w.).

TECHNICAL DIMENSION				**DIM. W.:**	**1**
Technical indicators	**Ind. w.**	**Sub-indicators**	**S-ind. w.**	**Factors**	**Factor w.**
T1. Removal efficiency (RE)	1	T1a. BOD T1b. TSS T1c. TN T1d. TP T1e. FC	1 1 1 1 1	T1-I. Monitoring RE T1-II. Removal efficiency T1-III. Long-term plan RE	1 2 1
T2. Operation and maintenance (O&M)	1	T2a. Pre-treatment T2b. Primary treatment T2c. Secondary treatment T2d. Tertiary treatment T2e. Disinfection	1 1 1 1 1	T2-I. Manuals T2-II. Short-term O&M T2-III. Long-term maintenance	1 1 1
T3. Sewer network functionality (SEW)	1	-	-	T3-I. Coverage T3-II. Design T3-III. Breakdown T3-IV. Hydraulic loading T3-V. Clogging T3-VI. Long-term plan SEW	2 2 1 2 1 1
T4. Reliability of the WWTP	1	-	-	T4-I. Design of the WWTP T4-II. Breakdown T4-III. Hydraulic loading T4-IV. Organic loading T4-V. Long-term plan WWTP	2 1 2 1 1
ENVIRONMENTAL DIMENSION				**DIM. W.:**	**1**
Environmental indicators	**Ind. w.**	**Sub-indicators**	**S-ind. w.**	**Factors**	**Factor w.**
E1. Potential safe reuse (SR)	1	E1a.Water E1b. Sludge	1 1	E1-I. Reuse practice E1-II. Monitoring SR E1-III. Safe reuse limits E1-IV. Long-term plan SR	1 1 2 1
E2. Eutrophication potential (EP)	1	E2a. TN E2b. TP	1 1	E2-I. Monitoring EP E2-II. Eutrophication potential E2-III. Long-term plan EP	1 2 1
E3. Effluent quality (EQ)	1	E3a. BOD E3b. TSS	1 1	E3-I. Monitoring EQ E3-II. Discharge limits E3-III. Long-term plan EQ	1 2 1
E4. Energy	1	-	-	E4-I. Energy-saving programme E4-II. Renewable energy	1 1
E5. Global warming potential	1	-	-	E5-III. Emissions reduction	-

Table 4-5. Cont'd

SOCIAL DIMENSION				**DIM. W.:**	**1**
Social indicators	**Ind. w.**	**Sub-indicators**	**S-ind. w.**	**Factors**	**Factor w.**
S1. Public health risk (PH)	1	-	-	S1-I. Exposure S1-II. Claims S1-III. Long-term plan PH	2 1 1
S2. Public awareness (PA)	1	-	-	S2-I. Ecological concerns S2-II: Public health concerns S2-III. Use of services S2-IV. Long-term plan PA	1 1 1 1
S3. Aesthetics (AES)	1	S3a. Smell S3b. Noise S3c. Visual impact	1 1 1	S3-I. Perception S3-II. Nuisance level S3-III. Action plan AES	1 2 1
S4. Public acceptance (PACC)	1	-	-	S4-I. Location of WWTP S4-II. Reuse practice S4-III. Long-term plan PACC	1 1 1
ECONOMIC DIMENSION				**DIM. W.:**	**1**
Economic indicators	**Ind. w.**	**Sub-indicators**	**S-ind. w.**	**Factors**	***Factor w.***
EC1. Tariffs	1	-	-	EC1-I. Tariff structure EC1-II. Documentation EC1-III. Follow-up	1 1 1
EC2. Operation and maintenance costs	1	-	-	EC2-I. Economic requirements EC2-II. Long-term investment EC2-III. Long-term plan O&M	1 1 1
EC3. Affordability (AF)	1	-	-	EC3-I. Payment of tariffs EC3-II. Payment capacity EC3-III. Strategy AF	1 1 1
INSTITUTIONAL DIMENSION				**DIM. W.:**	**1**
Institutional indicators	**Ind. w.**	**Sub-indicators**	**S-ind. w.**	**Factors**	**Factor w.**
I1. Institutional capacity (utility)	1	-	-	I1-I. Roles and responsibility I1-II. Procedures I1-III. Goals of the organization I1-IV. Long-term goals	1 1 1 1
I2. Institutional capacity (higher level)	1	I2a. Municipal I2b. Regional I2c. National	1 1 1	I2-I. Clear roles I2-II. External support	1 1
I3. Staff requirements (SR)	1	I3a. Operator I3b. Engineer I3c. Communicator I3d. Accountant I3e. Manager	1 1 1 1 1	I3-I. Availability I3-II. Level of expertise I3-III. Long-term plan SR	1 1
I4. Employee satisfaction	1	-	-	I4-I. Working conditions I4-II. Salary level	1 1
I5. Communication	1	-	-	I5-I. Use of services I5-II. Wastewater utility I5-III. Warnings regarding exposure risks	1 1 1

Results for CS7

The sustainability assessment for CS7 produced an overall sustainability score of 1.6 out of 4, which is a low level of sustainability (Table 4-6). This score shows that there are still many aspects that require improvement if the wastewater treatment system is to work effectively and be sustainable in the long-term. The technical dimension scored 1.8, social, economic and institutional dimensions scored 1.7 and the environmental dimension obtained the lowest score with 1.1. In this case study, only indicators such as Reliability and Aesthetics scored 3. All the indicators in the environmental dimension scored 1, with the exception of Effluent quality, which scored 2. This last indicator relates directly to the technical aspects of Removal efficiency, which scored 1, and Operation and maintenance and Sewer network functionality, each scoring 2. Public health risk and public acceptance, indicators within the social dimension received the lowest score of 1. As well as the economic indicator Affordability that scored 1. In the institutional dimension, the indicator in most need of improvement (i.e. a score of 1) was Communication.

The proportion of scores (i.e. 0, 1, 2, 3 and 4) obtained by all factors within each dimension for CS7 is presented in Figure 4-8. Results at the factor level show that some indicators in the environmental and economic dimensions received a score of 0, indicating that no information was available. Scores of 1 predominated, with 50% or more in the technical, environmental, social, and institutional dimensions, and 22% in the economic dimension. For instance, factor T1-I Monitoring (RE) within indicator T1 Removal efficiency scored 1 for all sub-indicators (i.e. BOD, TSS, TP, TN and FC) (Paper IV, Appendix C), meaning that improvements are needed in the WWTP to reach higher removal efficiencies for these constituents. Also, factors S1-I Exposure, S1-II Claims, and S1-III Long-term plan PH within indicator S1 Public Health risk, scored 1 (Paper IV, Appendix C), indicating that measures have to be taken to reduce Public health risk.

Table 4-6. Sustainability indicator scores for CS7.

Overall sustainability score 1.6									
Technical dimension	**1.8**	**Environmental dimension**	**1.1**	**Social dimension**	**1.7**	**Economic dimension**	**1.7**	**Institutional dimension**	**1.7**
T1. Removal efficiency	1	E1. Potential safe reuse	1	S1. Public health risk	1	EC1. Tariffs	2	I1. Institutional capacity (utility)	2
T2. Operation & maintenance	2	E2. Eutrophication potential	1	S2. Public awareness	2	EC2. Operation & maintenance costs	2	I2. Institutional capacity (higher level)	2
T3. Sewer network functionality	2	E3. Effluent quality	2	S3. Aesthetics	3	EC3. Affordability	1	I3. Staff requirements	2
T4. Reliability	3	E4. Energy	1	S4. Public acceptance	1			I4. Employee satisfaction	2
		E5. Global warming potential	1					I5. Communication	1

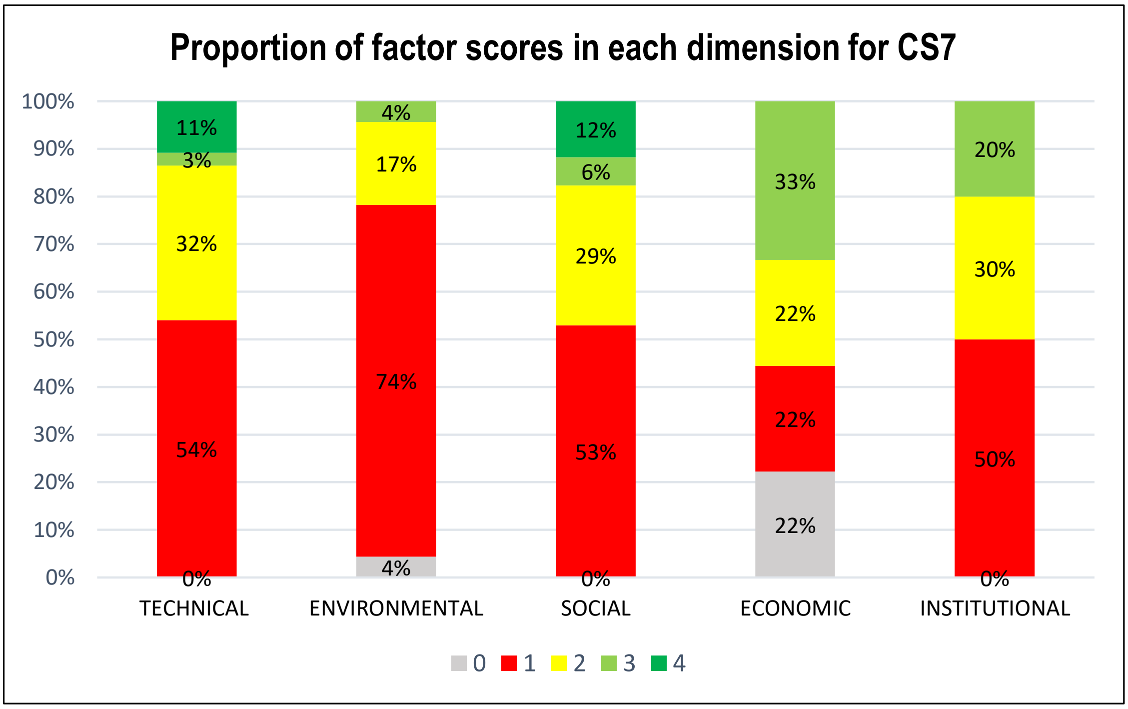

Figure 4-8. Proportion of factor scores in each dimension for CS7, expressed as percentages.

Results for CS8

The sustainability assessment for CS8 produced an overall sustainability score of 2.9 for the wastewater treatment system, which corresponds to a medium level of sustainability (Table 4-7). This level indicates that the components of the WWTS are working relatively well. The social dimension obtained a score of 3.4, the institutional dimension, 3.1, the technical dimension scored 2.9, the economic dimension obtained a score of 2.8 and the environmental dimension scored 2.4. The environmental indicators for Energy and Global warming potential scored 1. The indicators Sewer network functionality, Affordability, and Institutional capacity (higher level) scored 2, revealing scope for improvement. The indicators that received the highest score (4) were Reliability, Potential safe reuse, Public acceptance, Institutional capacity (utility), and Employee satisfaction. These results indicate that the WWTS is performing very well with regard to these indicators, that the management of the service is being conducted effectively and with adequate institutional capacity, and that employees are satisfied.

The proportion of scores received by all factors within each dimension for CS8 is presented in Figure 4-9. Scores of 4 and 3 predominate, but there are factors that scored 1 in four of the five dimensions. In the Environmental dimension, 24% of the factors scored 1, while in the Technical, Economic, and Institutional dimensions 14%, 13% and 11% of the factors respectively scored 1, respectively. Examples of factors that scored 1 within indicator T3 Sewer network functionality are: T3-II Design, T3-IV Hydraulic loading, T3-III Breakdown, T3-V Clogging, T3-VI Long-term plan SEW (Paper IV, Appendix C), which means that a long-term plan is required to improve the functionality of the sewer network in terms of design, reducing hydraulic loading, breakdowns and clogging. Within indicator E4 Energy, factors E4-I Energy saving programme, and E4-II Renewable energy scored 1 (Paper IV, Appendix C), suggesting that initiatives for a sustainable use of energy should be considered.

Table 4-7. Sustainability indicator scores for CS8.

Overall sustainability score 2.9									
Technical dimension	**2.9**	**Environmental dimension**	**2.4**	**Social dimension**	**3.4**	**Economic dimension**	**2.8**	**Institutional dimension**	**3.1**
T1. Removal efficiency	3	E1. Potential safe reuse	4	S1. Public health risk	3	EC1. Tariffs	3	I1. Institutional capacity (utility)	4
T2. Operation & maintenance	3	E2. Eutrophication potential	3	S2. Public awareness	3	EC2. Operation & maintenance costs	3	I2. Institutional capacity (higher level)	2
T3. Sewer network functionality	2	E3. Effluent quality	3	S3. Aesthetics	3	EC3. Affordability	2	I3. Staff requirements	3
T4. Reliability	4	E4. Energy	1	S4. Public acceptance	4			I4. Employee satisfaction	4
		E5. Global warming potential	1					I5. Communication	3

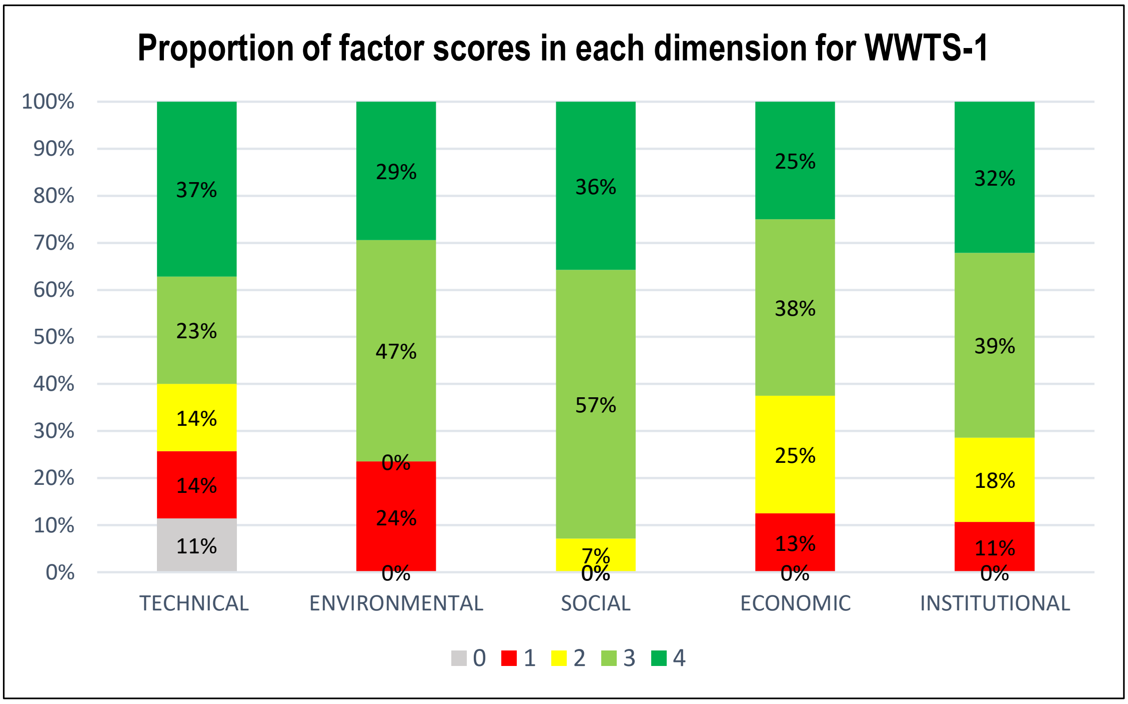

Figure 4-9. Proportion of factor scores in each dimension for CS8, expressed as percentages.

The sustainability assessment tool can generate a to-do list of improvements based on critical factors with scores of 0, 1 and 2. In this list generated by the tool, factors with scores 3 and 4 can also be identified to know what is working well. The detailed lists with low scores from these two cases can be found in (Paper IV, Appendix C). Based on the to-do list and the assessment process, strategies can be identified to improve the different areas related to the sustainability of the wastewater treatment system. When prioritizing strategies, the weighting can influence decisions about which measures should be taken first.

Radar plot graphs can facilitate comparison of assessment results of a system over time and can be used to visualize the progress achieved towards a sustainable level in all the dimensions. Figure 4-10 presents the radar plots for CS7 and CS8. In CS7, improvements are required to be implemented in order to raise the sustainability level of all dimensions from level 1 to level 4. In CS8, for instance still some efforts in the social dimension is required to fully reach the level 4 of sustainability.

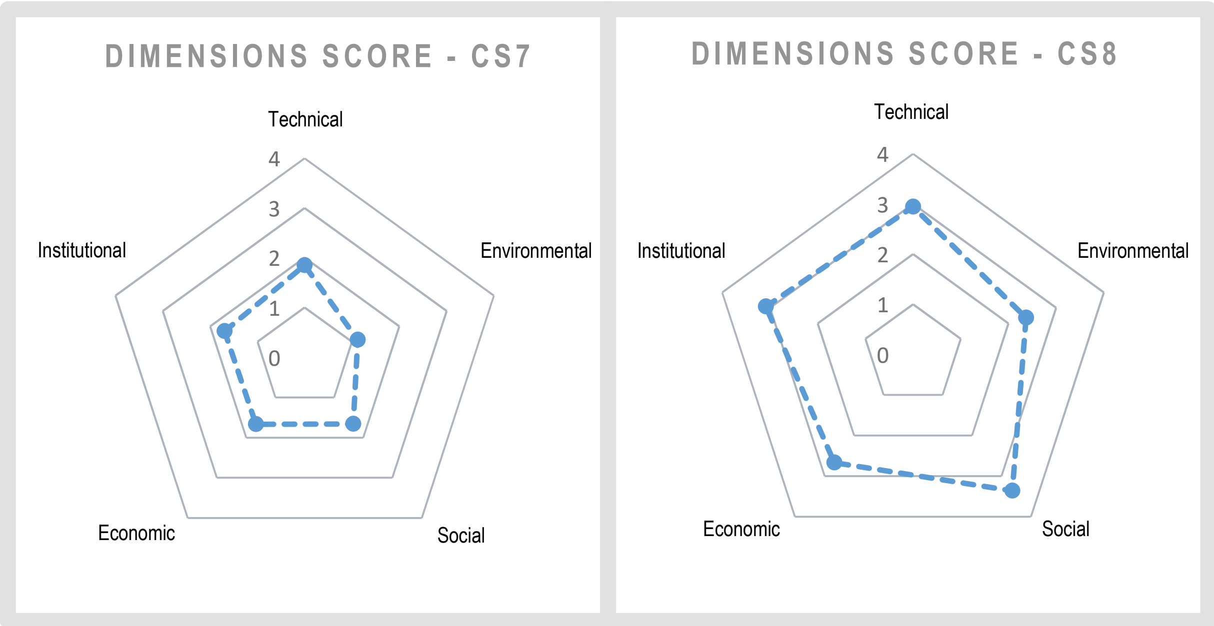

Figure 4-10. Radar plot graphs showing the results obtained for the sustainability assessment of CS7 and CS8.

Testing of the EVAS tool

The feedback from the application of the tool in the case studies was very positive. However, a number of potential improvements were identified during the course of the testing. For instance, regarding the assessment of the limits for compliance for safe reuse or eutrophication potential within the environmental assessment, it was suggested to enable the possibility to answer whether reuse or discharge is practiced with the effluent of the WWTS. In addition, in the case of reuse being practiced, there should be options to specify the compliance limits according to the type of crops irrigated. During the testing, it was also noted that the questions formulated to assess the factors included in each indicator could to some degree be misinterpreted by the assessor. The scoring based on quantitative data, included in the technical, environmental, and economic dimensions, was easier to assess in comparison with the qualitative data, e.g. the social dimension. The personal judgement of the assessors may have influenced the scores. It is therefore important to provide a more detailed description of the factors in relation to what is possible to measure in the field so that it is clear what is being asked. Also, it is important to discuss the results with multiple stakeholders or the entire staff that manages the WWTP to have a participatory assessment and results can be inherently validated.

Application of the EVAS tool in practice

An outline of a suggested framework within which the sustainability assessment can be carried out is presented in Figure 4-11. The suggested framework includes four main stages:

i. Identification of assessor or group of assessors. The assessor should preferably be the manager and the staff in charge of the main activities in the WWTS, although it might be needed also the participation from local stakeholders and external experts involved in the WWTS management. Assessors should be able to provide information for the assessment and input on the weighting of the variables of the tool (i.e. dimensions, indicators, sub-indicators and factors).

ii. Assessment of the current sustainability status of the WWTS using the EVAS tool. If necessary, participatory weighting of variables can be modified at this stage. The weighting may be useful to prioritize actions in the resulting to-do list or discuss with assessors the different perspectives among the components included in the assessment.

iii. Results from the assessment are revised by managers of the WWTS. Identification of aspects in the WWTS with a low level of sustainability support the prioritization of actions that can be implemented. Approved results should be documented to assure their quality and can be reported and communicated to the general public and decision-makers to motivate their support in the process of enhancing the sustainability of the systems.

iv. The tool could also be updated, and in that case further information would be included for implementing a new assessment. The manager of the WWTS should ideally update the assessment of the WWTS periodically.

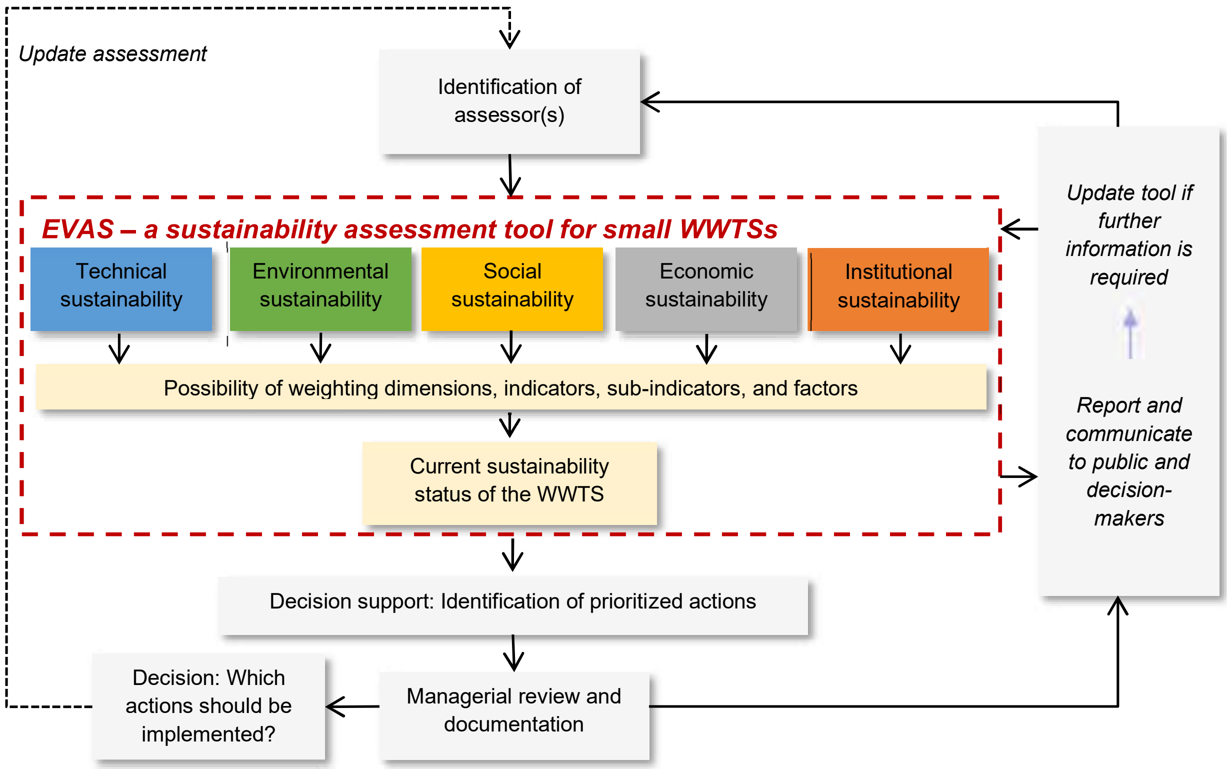

Figure 4-11. Outline of the proposed sustainability assessment framework, adapted from (Rosén et al., 2015)

The suggested framework should be an iterative working process. The assessment may require additional data collection and it can be updated as new data becomes available. To facilitate quality assurance, the assessment must be fully documented and communicated. When decisions are made about implementing strategies, the assessment can be updated and followed up over time to record improvements in the sustainability of the WWTS.

5 DISCUSSION

This section includes a discussion based on the main findings from the studies developed for this thesis. The discussion highlights critical aspects that need to be considered when assessing the sustainability of small wastewater treatment systems in the context of low and lower-middle income countries.

5.1 Performance of small WWTPs and their impact

In the case studies included in this thesis it was found that wastewater irrigation is a common practice due to water scarcity and increased crop yields resulting from the fertilization benefits of using wastewater. In Paper I, it was shown that the low performance of the WWTPs results in poor-quality effluents. Consequently, in Paper II the impact on human health and the ecological risks were estimated in relation to the management of the WWTPs. Results showed that better management and performance of the WWTPs will reduce the microbial risks estimated for Enterovirus and *A. lumbricoides.* However, additional treatment is needed to reduce the risks related to *Salmonella spp* to acceptable levels. It is important to design wastewater treatment systems based on the pathogenic load that needs to be reduced, especially if the effluent is to be used for food production. As regards ecological risks associated with nitrogen and phosphorus accumulation in soils, additional technologies to remove nutrients are needed to reduce these risks. It is crucial to monitor the performance of the WWTPs and the quality of the effluents in order to determine if there is a need to reduce these risks. Lack of monitoring of the quality of reused effluent is generally a limitation in low and lower-middle income countries (Razzolini et al., 2020). Mitigation of risks to human health and ecological risks could in turn imply a need to improve the management of the WWTPs, upgrade the technologies, or communicate possible risks to farmers, consumers, and local authorities. A limitation identified in the case studies was the lack of specific regulations in Bolivia to control the practice of irrigation using wastewater. The results from Paper I and Paper II showed that efforts on the part of planners and managers must take account of relevant aspects when managing wastewater (e.g. adequate technologies, local expertise, information to users, cost of operation and maintenance) in order to ensure sustainable WWTPs. This sustainable approach will require planners to rethink the level of treatment and the types of technologies used in an effort to reduce contaminant levels.

A major limitation found in the case studies was that the WWTPs did not have monitoring data to evaluate their performance. Lack of data on wastewater treatment coverage and monitoring of existing WWTPs is a common issue in low and lower-middle-income countries (Malik et al., 2015; Massoud et al., 2009; WHO, 2018). Technologies such as Imhoff tanks were used, mainly because they had been used in other small towns or villages. However, no assessment was made to evaluate their functionality to determine whether it is an adequate technology that could work optimally in the local context. Periodic monitoring and performance assessments are crucial (Massoud et al., 2009), especially when new technologies are introduced to avoid failures resulting from the type of technology used, or the design, construction, operating, and maintenance requirements. Low and lower-middle income countries not only face challenges when setting up more wastewater treatment systems in general, but also when old technologies that do not work are not replaced, i.e. Imhoff tanks (Oakley and Salguero, 2011). On the other hand, technologies such as stabilization ponds were found to be less likely to fail due to their minimal operating and maintenance requirements (Paper I and Paper II), although smell issues reported by users in CS3 were a constraint. There is a need to implement new wastewater treatment systems, and to upgrade and enlarge existing systems to achieve a high level of pollutant removal from wastewater for safe discharge or reuse. The planning and design of the WWTS should take into account all local resources available, especially financial and technical resources, to ensure the technologies that are introduced will work optimally and fulfil their purpose.

In general, all WWTPs assessed were overloaded in terms of hydraulic and organic loading (Paper I). Monitoring, operation, maintenance, and technical assessment are crucial to guarantee the facilities have the required capacity for the actual load entering the plant. The planning component should anticipate when the WWTP needs to be enlarged, as the population served by the WWTP increases. Another reason WWTPs are not performing optimally is the lack of operation and maintenance and technical expertise, as concluded in Ujang & Buckley (2002). The selection of technologies should therefore take account of the local human resources available for their functionality in the planning phase (McConville et al., 2011). It is also a case of ensuring sufficient financial resources are available to hire staff with the necessary expertise, e.g. technicians or engineers. Operators must be provided with training, manuals need to be available, and procedures need to be in place to ensure adequate operation and maintenance. It is crucial that local expertise and capacity are developed to manage wastewater treatment systems adequately.

It is also important that users are aware of the need to pay a tariff that covers the cost of providing a good level of service and that it should be affordable. In the case studies involving villages it was seen that there is a sense of ownership and responsibility regarding the service, whilst in small towns it is more about paying a fair tariff for what the service represents in terms of cost. The semi-structured interviews with users showed in general that awareness of the importance of having a good level of service is higher in villages. The users are directly involved in the management of the WWTS and can see the negative implications if the WWTP is not performing adequately. In small towns it is not the case, as users expect, that the organization in charge must assume responsibility as part of the service. A common issue reported in both groups was the nuisance level from the smell generated by the WWTP. Based in their observations, most users in villages reported that the WWTP was working well. In small towns the two predominant answers were 'Don't know' and 'The WWTP is working badly'. It might be possible that users in small towns associated the poor reported functioning of the WWTP with the smell issue. In small towns, this might in turn discourage paying the tariff that is necessary as their perception is that the service is causing problems. Information to users is required to raise the level of awareness of the financial requirements in order to have a WWTP that is functioning adequately and thus providing a good level of service, both in the collection and treatment of wastewater. It was evident throughout the study that management of WWTSs in small towns is challenging in the light of the transition from village to small town. This supports the need for a management model that falls somewhere between a community-based organization and a public/private utility in a city (Pilgrim et al., 2007; Cossio et al., 2017a). The structure of such a model should ensure optimal performance by incorporating elements that were successful on a smaller scale and adapting them to management on a larger scale that would be required with a small town facility. Users should be informed about the need for adequate operation and maintenance of the sewer network and WWTP to safeguard human health and the environment. The institutions in charge of the "new management model" should therefore apply mechanisms that ensure the technical, social, financial and environmental aspects are better integrated to achieve sustainable wastewater treatment systems.

5.2 Sustainability of small WWTPs in the context of Bolivia

The initial work presented in this thesis identified a clear need to develop locally relevant monitoring indicators for sustainability. The need for more contextualized indicators is supported by other authors, who have developed assessment tools that have incorporated local conditions. Benavides et al. (2019) highlights the need to account for the limited availability of data for assessment when identifying relevant indicators, and Brunner et al. (2018) highlights the need to pinpoint key aspects when implementing successful projects relevant to the local context. In the context of the case studies in Bolivia, which is a lower-middle income country, the relevant dimensions for contextualized sustainability indicators were found to be: Institutional, Social, Economic, Technical, and Environmental. The key aspects found in each sustainability dimension are discussed below.

Institutional dimension

The institutional dimension was ranked as the most important dimension by the local experts involved in this study. There is still a lack of organizational structure regarding regulations, monitoring and management to deal with wastewater treatment. Having a good organizational structure at the utility level will make it possible to implement or improve other aspects related to the sustainability of the WWTS. Furthermore, institutions at higher levels (i.e. municipalities, regional departments, and national entities) need to be aware of the operating status of the WWTS and what is required to achieve more sustainable wastewater management. Municipal authorities are by law responsible for basic service provision (i.e. water and sanitation) to the population, but once they hand over management of the infrastructure to a local organization there is no technical assistance or follow-up of the organization to ensure the WWTS continues to perform as expected. The regional department must also fulfil its monitoring duties fully, ensuring that the WWTS is complying with national discharge regulations, although limited resources make it difficult to reach all the WWTSs. The Ministry of Environment and Water is responsible for formulating plans, guidelines, norms, and regulations to ensure basic services are being provided throughout the country. However, despite the nationwide efforts that have been made in partnership with external bodies since 2013 to improve wastewater management, there are still areas that require further development, such as regulations for farmers to ensure safe use of wastewater. Better communication and cooperation between higher level institutions must be achieved if progress is to be made in achieving sustainability.

Social dimension

The social dimension has been recognized as one of the important dimensions in achieving sustainability (Popovic et al., 2013), especially when implementing technologies in the context of low and lower-middle income countries (Lehmann et al., 2013). The systematization of sustainability indicators carried out for the purposes of this thesis lists twelve social indicators, although only Public acceptance and Aesthetics could be identified as standard indicators (Paper III). Mahjouri et al. (2017) argue that the reason social sustainability indicators are ignored in some studies is due to the difficulty encountered when measuring them. This uncertainty was also confirmed while testing the EVAS tool in this thesis. However, efforts have been made to develop assessment methods and identify social indicators that can be measured quantitatively (Popovic and Kraslawski, 2018; Padilla-Rivera et al., 2016). Social indicators are critical, especially in the context of low and lower-middle income countries, not least because they are connected to the financial capacity to pay an adequate tariff to sustain effective management of the service. As regards the Aesthetics, the sub-indicator Smell was reported to be one of the main issues in both types of case study, i.e. villages and small towns, and this is something that should be taken into account when asking users to pay a tariff that is sufficient, as smell can be associated with the malfunctioning of the WWTP. The same applies to contamination of streams when poor-quality effluent is discharged, especially in areas where water is scarce. As users could very well have financial priorities other than paying for this service, public acceptance is a critical indicator in low and lower-middle income countries if the technology is to be implemented and if its sustainability over time is to be supported (Helgegren et al., 2018; Biemba et al., 2017). It is known also that the public health risk is another main driver behind having sustainable services that work satisfactorily. Public awareness is key to the adequate functioning of the WWTS. In the study it was found that a higher level of public awareness regarding the need for correct use of the sewer network could mitigate issues such as overflows due to blockages in the network resulting from incorrect use, as reported in CS5. The assessor of CS8 (Paper IV) suggested that a good strategy for achieving payment of adequate tariffs by users could be informing them about what is required if the WWTP is to be operated and maintained efficiently and enlarged if necessary. This could potentially have a positive impact on the users' willingness to pay a higher tariff. Furthermore, there should be open and constantly updated information from the managers of the WWTSs to the public on how the system is performing.

Economic dimension

It is critical that the income from the tariffs that are paid cover all the operating and maintenance costs and are sufficient to ensure future replacement or enlargement of the WWTSs. From the users' point of view, the Affordability indicator used in the tool aims to check whether or not the users are capable of paying the tariffs required for the service. Other authors argue that willingness to pay is also a critical factor behind having a sustainable level of service, as it is a reflection that the service is responding to the real demands of the users and that the benefits deriving from it are recognized (Birol and Das, 2012; Vásquez et al., 2009). This becomes more critical in the context of low and lower-middle income countries where sometimes paying an adequate tariff, even for the obvious benefits of having a drinking water system, is a challenge (Ceric and Vucijak, 2011; Whittington, 2010). The assessment of indicators such as Affordability and Willingness to pay therefore require further investigation if they are to be applied. In the current study, the intention was to investigate willingness to pay for a better service through the semi-structured interviews with users. Results were very vague as users would reply positively, but there was no evidence that they would pay in practice. Willingness to pay could be added to the tool in order to improve the assessment of the economic dimension in relation to the sustainability of a WWTS. However, the same considerations as for social indicators should be taken into account to measure these types of qualitative indicators more objectively (Paper IV).

Technical dimension

In recent studies conducted in high or upper-middle income countries, the Removal efficiency indicator is often included in the environmental dimension as an indication that technologies are working adequately (Molinos-Senante et al., 2014). In the case studies it was confirmed that it is still a challenge to reach acceptable levels of removal efficiency in relation to the theoretical values of the technologies implemented (Paper I). This indicator was therefore included in the technical dimension to emphasize that this issue must be addressed in the context of low and lower-middle income countries. However, in addition to implementing actions prompted by the to-do list generated in the tool, improving the removal efficiency of a WWTS requires the technologies at some of the WWTSs to be upgraded if they are to achieve health-based targets (Paper II).

During the process for contextualizing the sustainability indicators, it became clear that it was not possible to assess the sustainability of WWTPs without also considering sewer network functionality as an important indicator. It was therefore included in the list of contextualized indicators and in the EVAS tool (Papers III and IV). This indicator is vital to ensuring that the raw wastewater is collected adequately at the users' site, and that it is transported and reaches the WWTP for treatment. Correct use of the sewer network will support the reduction of clogging or blockages in the network and at the WWTP by preventing large solids or grease from entering the system. On the other hand, the standard indicator Reliability of the WWTP was not highlighted in the contextualization of indicators from a local point of view. Nonetheless, including it in the assessment tool might contribute to building up technical knowledge and capacity among local managers to achieve more sustainable WWTSs.

Environmental dimension
In the context of this study, the testing of the EVAS tool in two case studies suggested that the indicators Potential safe reuse, Eutrophication potential, and Quality of effluent are more relevant for the WWTS managers to assess compared to Energy and Global warming potential. The relevance of the first three indicators might be because they relate to the issues of contamination of the environment and public health risks. Managing a WWTS thus requires fulfilment of the targets formulated for these indicators to ensure reuse practices are implemented safely, waterbody recipients are protected, and public health is safeguarded. In particular, potential safe reuse requirements should be achieved to safely implement resource recovery practice within the new paradigm of a circular economy (Larsen et al., 2009). Nevertheless, the inclusion of standard indicators such as Energy and Global warming potential could encourage local managers or authorities to take more integrated measures aimed at achieving sustainability.

5.3 Sustainability assessment of small WWTSs in practice

The sustainability of small wastewater treatment systems can be enhanced by understanding and identifying all the relevant aspects that are essential to it (Jones and Silva, 2009). Merging theoretical knowledge with empirical knowledge from the field allows for the practical application of the indicators when assessing small wastewater treatment systems (Benavides et al., 2019). The assessment tool was designed to identify weak areas for improvement by assessing local data. However, if data were not available, the tool suggests which type of data would be useful for managers to collect in order to assess the sustainability of their WWTSs and view their improvement over time. Furthermore, the tool can be adapted by modifying the weightings for specific conditions in each system, thus providing more site-specific results to improve its sustainability. The sensitivity analysis carried out using three different weighting scenarios showed that the tool is not sensitive to these changes. Difference in weightings can help managers – using the resulting to-do list with scored factors from the EVAS tool assessment – to identify those measures that require greater prioritization by allocating resources to the factors with higher weightings.

The aim of the sustainability assessment tool EVAS is to provide effective support to managers of the wastewater treatment systems, helping them to improve the performance and sustainability of their WWTSs. A further aim is to communicate the results to decision-makers to support them in their identification of strategies to improve wastewater management practice. Several authors highlight the need to engage local stakeholders at the decision-making level, allowing them to support and incorporate the sustainability assessment in practice to improve the WWTS in the operating phase (Lundie et al., 2008; Bao et al., 2013; Sawaf and Karaca, 2018). The active participation of key stakeholders involved in wastewater management was particularly important for the studies, as validation was required. In the case studies carried out, this validation took the form of presenting key stakeholders with the results relating to the treatment efficiency of their WWTPs, along with recommendations for improvement. The process adopted in the research and the delivery of results to the board of members and managers facilitated a process of mutual learning, focusing on ways in which the management of the WWTPs could be improved. Papers III and IV in this thesis have demonstrated that contextualization and the testing process in the field are critical to assuring the effectiveness of the indicators used in the assessment, and the way they are measured and interlinked to present the results. This reinforces the assertion that achieving sustainable services involves a process in which knowledge and practical solutions are created by identifying critical aspects in a participatory way (Cuppens et al., 2013).

6 CONCLUSIONS AND FUTURE WORK

This section presents the overall conclusions of this thesis, highlighting the main contribution made, formulating recommendations based on the results obtained, and suggesting areas in which work could be carried out in the future.

This thesis contributes to expanding the knowledge base regarding sustainability of wastewater treatment in low and lower-middle income countries, thus linking the low number of studies conducted in this context with the extensive research conducted in high and upper-middle income countries. It is believed that the EVAS tool that has been developed can support local wastewater managers and decision-makers in this context as a means of identifying strategies and a plan for improvements based on the results of the assessment and with the ultimate aim of achieving more sustainable wastewater treatment systems.

The most important conclusions from this PhD thesis are as follows:

- The small wastewater treatment systems investigated in this study are not performing optimally, mainly due to lack of or deficient operating and maintenance practice, but also due to a lack of funding to cover operating costs, especially to hire staff with the required level of expertise or to cover monitoring costs.

- Matching the operating and maintenance requirements for the type of technology used to the level of local expertise is critical. Maintenance of Imhoff tanks presented technical difficulties whereas stabilization ponds with lower operating and maintenance requirements performed better and proved to be more resilient.

- Improvement in sewer network functionality was identified as a key element if optimal performance of the WWTPs is to be achieved, along with the introduction of an adequate pre-treatment unit.

- Optimal operation and maintenance of small wastewater treatment systems can potentially reduce human health risks associated with wastewater irrigation, whereas non-optimal performance due to poor operation and maintenance can lead to greater risks compared to irrigation using raw wastewater.

- Ecological risks due to accumulation of nitrogen and phosphorus in soil from reusing treated wastewater can be prevented by ensuring that small wastewater treatment plants perform optimally.

- Performance and management assessments carried out at the WWTPs suggest that robust technologies with low operating and maintenance requirements, and sufficient levels of treatment at the WWTSs (i.e. primary, secondary, tertiary and disinfection) are required to achieve a high degree of efficiency in the removal of contaminants from wastewater to ensure safe discharge or reuse.

- In the context of low and lower-middle income countries the institutional dimension was considered to be particularly critical by local stakeholders in enabling technical performance, and achieving environmental goals, positive social interaction, acceptability, and financial viability.

- The performance of small wastewater treatment systems should be monitored on a regular basis to allow managers to take steps to improve it if necessary and allow decision-makers to formulate strategies to ensure public health and the environment are safeguarded.

- The sustainability assessment tool EVAS, developed to assess small wastewater treatment systems in low and lower-middle income countries, has the potential to support the analysis of current status in the operational phase and to support identification and prioritization of strategies for further improvement.

Recommendations and suggestions for future work based on this study are as follows:

- The characteristics of a system can change over time, or new sustainability indicators could be identified, thus a revision and update of the list of indicators and the assessment tool could be necessary in the future.

- The functionality and sustainability of the collection system should be further investigated to better integrate all the aspects that contribute to optimal performance in the EVAS tool for assessing the sustainability of the WWTS.

- Future research on how the operation and maintenance of existing wastewater treatment technologies could affect human health and the ecological risks arising from wastewater irrigation practice should be conducted with a focus on other emerging contaminants, such as pharmaceutical components, pesticides, and microplastics.

- Further investigation should be done on how the social indicators, e.g. public acceptance, public awareness, and user affordability, can be measured more objectively, by implementing social studies to allow a deeper understanding on the factors that influence them.

- It is recommended that researchers in cooperation with practitioners continue to work towards adapting the tool for planning purposes, or for comparing measures to support prioritization more effectively.

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APPENDICES

This section contains Appendix A, Appendix B and Appendix C. Appendix A includes the layout of the semi-structured interviews designed to collect data from users (i.e. A1. Households, A2. Institutions, and A3. Farmers). Appendix B includes the monitored data from the WWTPs in CS1-5 in Paper I. Appendix C includes calculations in the EVAS tool.

APPENDIX A.

A1. Layout of the semi-structured interviews with households

DATA TO IDENTIFY THE INTERVIEWEE

Interview date:
Location of the household:
Name and age of the interviewee:
Position of the interviewee (if applicable, e.g. board member or leader):
Name of the interviewer:

GENERAL DATA ON THE WATER AND WASTEWATER TREATMENT SYSTEMS

1. What type of water supply system do you have?

   Drinking water system ☐
   Spring ☐
   Well ☐
   River ☐ Name of the river:
   Private water source ☐ Specify:
   Other ☐ Specify:

   If the interviewee has a drinking water system, continue with the following questions:

2. Does your household have a water meter?
   ☐ Yes ☐ No
   If the answer is Yes, please answer the following questions:
   a. What is your average monthly consumption [m^3]?
   b. How much do you pay each month for the water service [Bs]?

3. Please select the ways in which you use the water system.

- Toilet ☐
- Shower ☐
- Washing clothes ☐
- Kitchen ☐
- Irrigation ☐

4. Does the system provide you with enough water?
   ☐ Yes ☐ No
   If the answer is No, please explain:

5. Do you have a sanitation facility?
   ☐ Yes ☐ No
   If the answer is Yes, please choose the system you have.
   a. Flush toilet connected to a sewer network ☐
   b. Flush toilet with a septic pit ☐
   c. Flush toilet with an infiltration pit ☐
   d. Latrine with a septic pit ☐
   e. Dry latrine ☐
   f. Other (specify) ☐

Continue only if the interviewee has a flush toilet connected to the sewer network.

FUNCTIONING OF THE SEWER NETWORK AND THE WASTEWATER TREATMENT PLANT (WWTP)

6. How much do you pay for the sewer network service?

7. Is the sewer network working well? ☐ Yes ☐ No ☐ Don't know
   If the answer is No, please explain the issues and who solves them?

8. Is the sewer network connected to a WWTP? ☐ Yes ☐ No ☐ Don't know

9. Do you have information about the WWTP? ☐ Yes ☐ No
   If the interviewee answered Yes, questions 10-18 must also be answered

10. How is the WWTP working now?
    Well ☐
    Badly ☐
    Don't know ☐
    Other ☐ Specify:

11. How does the WWTP need to be improved?

12. Who should be responsible for making these improvements?

13. If the water association needs to improve the sewer network service and wastewater treatment in the future, are you willing to pay a higher tariff?
    ☐ Yes ☐ No
    If the answer is No, please explain:

ENVIRONMENTAL EFFECTS

14. Do you consider it important to have a WWTP? ☐ Yes ☐ No
    Please give reasons for your answer:

15. Does the WWTP produce a smell?
    ☐ Yes ☐ No ☐ Don't know

16. Is the WWTP noisy?
    ☐ Yes ☐ No ☐ Don't know

17. Does the WWTP affect the landscape?
    ☐ Yes ☐ No ☐ Don't know

    If questions 15-17 were answered with a Yes, please provide more details (e.g. smell at what hours of the day; how far away the WWTP is from the home; the type of noise that is generated; how it affects the landscape, etc.):

18. Do you accept the WWTP?
    ☐ Yes ☐ No
    Please give reasons for your answer:

19. Do you know where effluent from the WWTP is discharged?
    ☐ Yes ☐ No
    If the answer is Yes, please explain (e.g. if it is into a river, name the river and state during which seasons):

20. Do you know if families or farmers use effluent from the WWTP?
    ☐ Yes ☐ No
    If the answer is Yes, how do they use it? If it is for irrigation, which crops do they irrigate?

21. Do you know if use of effluent has caused infection in children or farmers who live close to the WWTP?
☐ Yes ☐ No
If the answer is Yes, please explain:

22. Do you know if use of effluent has caused any problems for animals raised in the areas close to the WWTP?
☐ Yes ☐ No
If the answer is Yes, please explain:

COMPLEMENTARY DATA

23. How many people in the household use the basic services?

24. What is the occupation of the head of the household?

25. What is the monthly income of the head of the household?

A2. Layout of the semi-structured interviews to institutions

The layout was the same as for households, but with the following additions:

On average each month, how many people at your institution use the basic services (i.e. water and toilets)?

Do you have a sanitation facility?

☐ Yes ☐ No

If the answer is Yes, please state the type of technology you have.

a. Flush toilet connected to a sewer network ☐ Number:
b. Flush toilet with a septic pit ☐ Number:
c. Flush toilet with an infiltration pit ☐ Number:
d. Latrine with a septic pit ☐ Number:
e. Dry latrine ☐ Number:
f. Other (specify) ☐ Number:

How does your institution dispose of the wastewater from the toilets?

COMPLEMENTARY DATA

For health centres:

Please provide the following details of cases registered during the past six months attributable to consumption of water and food contaminated as a result of using effluent from the WWTP?

a. Diarrhoea ☐
b. Parasitism ☐
c. Stomach infection ☐
d. Dermatitis ☐

A3. Layout of the semi-structured interviews with farmers

The layout was the same as for households, but with the following additions related to irrigation practices:

Do you irrigate your crops using effluent from the WWTP? ☐ Yes ☐ No

Where do you access effluent from the WWTP to irrigate your crops?

Which crops do you irrigate using effluent from the WWTP?

How frequently do you irrigate using effluent from the WWTP?
All year round ☐
In the dry season ☐
Other ☐ Specify

Why do you use effluent from the WWTP?

What are the benefits of using effluent from the WWTP on your crops?

Do you know if effluent from the WWTP is used for other purposes downstream?

APPENDIX B.

MONITORED DATA FOR CASE STUDY 1 - WWTP

Sampling date	Spot sampling	TSS mg/L	BOD mgO_2/L	COD mgO_2/L	Faecal coliforms UFC/100 ml
19-02-2014	Influent	143	87	89	1.50E+07
	Effluent-Imhoff tank	146	68	89	3.00E+07
	Effluent-Biofilter	32	21	98	2.20E+07
	Effluent	137	80	80	1.40E+07
09-05-2014	Influent	248	178	271	3.60E+07
	Effluent-Imhoff tank	190	263	440	1.20E+07
	Effluent-Biofilter	178	301	431	1.90E+07
	Effluent	186	307	409	1.00E+07
19-08-2015	Influent	232	435	528	3.00E+07
	Effluent	281	440	548	1.90E+07
04-11-2015	Influent	553	994	1,054	2.10E+07
	Effluent	18	389	434	2.70E+07

MONITORED DATA FOR CASE STUDY 2 - WWTP

Sampling date	Spot sampling	TSS mg/L	BOD mgO_2/L	COD mgO_2/L	Faecal coliforms UFC/100 ml
11-08-2015	Influent	103	402	842	1.00E+07
	Effluent	165	604	790	1.10E+07
04-11-2015	Influent	221	186	273	1.00E+07
	Effluent	236	345	470	5.00E+06
21-04-2016	Influent	96	177	606	4.00E+07
	Effluent	129	158	405	4.90E+07
03-08-2016	Influent	212	221	376	4.00E+06
	Effluent	94	259	368	1.40E+07

MONITORED DATA FOR CASE STUDY 3 - WWTP

Sampling date	Spot sampling	TSS mg/L	BOD mgO_2/L	COD mgO_2/L	Faecal coliforms UFC/100 ml
13-08-2015	Influent	652	540	923	3.80E+07
	Effluent-Anaerobic pond 1	90	236	413	5.50E+06
	Effluent-Anaerobic pond 2	84	133	347	4.00E+06
	Effluent-Facultative pond 1	90	164	250	4.00E+05
	Effluent-Facultative pond 2	262	162	203	2.90E+06
	Effluent-Maturation ponds	78	206	236	1.10E+06
18-11-2015	Influent	636	846	904	9.00E+07
	Effluent-Anaerobic pond 1	92	266	296	4.00E+06
	Effluent-Anaerobic pond 2	88	282	313	9.70E+06
	Effluent-Facultative pond 1	178	222	297	8.00E+05
	Effluent-Facultative pond 2	116	228	246	3.80E+06
	Effluent-Maturation ponds	122	165	234	1.10E+06

CONT'D - MONITORED DATA FOR CASE STUDY 3 - WWTP

Sampling date	Spot sampling	TSS mg/L	BOD mgO_2/L	COD mgO_2/L	Faecal coliforms UFC/100 ml
03-03-2016	Influent	600	512	578	4.90E+07
	Effluent-Anaerobic pond 1	134	161	182	2.90E+06
	Effluent-Anaerobic pond 2	116	131	176	6.50E+06
	Effluent-Facultative pond 1	186	219	229	2.90E+06
	Effluent-Facultative pond 2	1,127	194	237	3.70E+06
	Effluent-Maturation ponds	148	150	175	1.10E+06
04-08-2016	Influent	940	559	874	2.20E+07
	Effluent-Anaerobic pond 1	88	110	287	7.80E+07
	Effluent-Anaerobic pond 2	88	177	268	2.00E+06
	Effluent-Facultative pond 1	28	143	193	3.00E+06
	Effluent-Facultative pond 2	62	112	182	2.00E+06
	Effluent-Maturation ponds	40	147	195	1.00E+06

MONITORED DATA FOR CASE STUDY 4 - WWTP

Sampling date	Spot sampling	TSS mg/L	BOD mgO_2/L	COD mgO_2/L	Faecal coliforms UFC/100 ml
19-02-2014	Influent	284	98	137	3.90E+06
	Effluent	31	23	86	4.70E+06
09-05-2014	Influent	148	95	183	2.90E+06
	Effluent	14	118	441	4.00E+06
19-08-2015	Influent	184	274	320	4.00E+06
	Effluent	26	308	399	8.00E+06
04-11-2015	Influent	120	421	457	3.30E+06
	Effluent	532	422	474	7.10E+06

MONITORED DATA FOR CASE STUDY 5 - WWTP

Sampling date	Spot sampling	TSS mg/L	BOD mgO_2/L	COD mgO_2/L	Faecal coliforms UFC/100 ml
11-08-2015	Influent	169	258	612	4.20E+06
	Effluent-Imhoff 1	130	200	348	8.00E+05
	Effluent-Imhoff 2	24	273	386	1.00E+06
04-11-2015	Influent	11	88	142	3.50E+06
	Effluent-Imhoff 1	271	72	146	7.80E+06
	Effluent-Imhoff 2	31	69	79	9.80E+06
20-04-2016	Influent	103	84	129	1.50E+07
	Effluent-Imhoff 1	166	128	215	2.30E+07
	Effluent-Imhoff 2	78	102	128	1.60E+07
	Effluent	92	92	122	9.90E+06
03-08-2016	Influent	148	147	268	3.20E+07
	Effluent-Imhoff 1	36	128	139	4.00E+06
	Effluent-Imhoff 2	266	113	117	4.00E+06
	Influent	168	84	115	5.00E+06

APPENDIX C.

Calculations in the EVAS tool

Each factor (f) in the EVAS tool is a assigned a score (S_f) by the user between 0 and 4 according to the traffic light scale, and a weight (W_f) according to the importance of the factor. Standard weights in the EVAS tool are 1 or 2, but any number can be set by the user if motivated: the higher the number the higher importance of the factor (sub-indicator, indicator, or dimension). The normalised weight ($w_{f,si}$) of each factor under each sub-indicator (si) is calculated as:

$$w_{f,si} = \frac{W_{f,si}}{\sum_{f=1}^{F} W_{f,si}} \quad \text{Eq. C-1}$$

The sub-indicator scores (S_{si}) are then calculated as a weighted sum:

$$S_{si} = \sum_{f=1}^{F} w_{f,si} S_f \quad \text{Eq. C-2}$$

Each sub-indicator is also given a weight (W_{si}) according to the relative importance of the sub-indicator and a normalised weight ($w_{si,i}$) is calculated for each sub-indicator included in an indicator (i) as:

$$w_{si,i} = \frac{W_{si,i}}{\sum_{si=1}^{SI} W_{si,i}} \quad \text{Eq. C-3}$$

The indicator scores (S_i) are calculated as:

$$S_i = \sum_{si=1}^{SI} w_{si,i} S_{si} \quad \text{Eq. C-4}$$

According to the same principle, each indicator is given a weight (W_i), and the normalised weight ($w_{i,d}$) of each indicator under each dimension (d) is calculated as:

$$w_{i,d} = \frac{W_{i,d}}{\sum_{i=1}^{I} W_{i,d}} \quad \text{Eq. C-5}$$

The dimension scores (S_d) are calculated as:

$$S_d = \sum_{i=1}^{I} w_{i,d} S_i \quad \text{Eq. C-6}$$

Each of the five dimensions is given a weight (W_d), and the normalised weight (w_d) of each dimension is calculated as:

$$w_d = \frac{W_d}{\sum_{d=1}^{D} W_d} \quad \text{Eq. C-7}$$

Finally, the overall score (S_o) of the EVAS tool is calculated as:

$$S_o = \sum_{d=1}^{D} w_d S_D \quad \text{Eq. C-8}$$

Further, in the EVAS tool, there are two types of logical functions related to the calculations of the scores included, listed below.

- If there is no monitoring at all regarding any sub-indicator relating to factors T1-I, E1-II, E2-I, and E3-I, the resulting score of that sub-indicator becomes 0.
- If targets are reached for a sub-indicator on a medium or high level, the last factor of that sub-indicator relating to implementation of long-term plans is regarded as not relevant (n.r.) and left out of the assessment. This relates to indicators T1, T3, T4, E1, E2, E3, S1, S2, S3, S4, EC2, I3, I5.