Article

Co-Generating Knowledge in Nexus Research for Sustainable Wastewater Treatment

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Abstract: Currently installed wastewater treatment systems in many developing countries are unsustainable, failing in either the social, economic or ecological dimension of sustainability. Nexus research looking at resources involved in wastewater treatment could support the transition towards more sustainable systems. Nexus thinking aims to overcome bio-physical systems thinking by including transdisciplinary research methods. Approaches for integrating results from different types of analysis and disciplinary backgrounds are scarce and have not been described extensively in nexus research. Transdisciplinary research suggests creating system, target and transformation knowledge as a common framework to describe meaningful transformations. Our goal is to show how a better understanding of the level of knowledge created by different types of analysis can pave the way towards integrating results for sustainability. In this article, three types of analysis, namely sustainability assessment, stakeholder perspective analysis and wickedness analysis, were applied in two pilot case wastewater treatment systems in Latin America. Through a three-step process, generated knowledge was assessed for each type of analysis individually while also highlighting synergies between them. The results demonstrate that structuring results by generated knowledge type can help combining outcomes in a meaningful manner. The findings show that technical flaws are present and fixable, and that issues relating to behaviours or values are more challenging to address but arguably more meaningful for systemic change.

Keywords: sustainability assessment; wickedness analysis; stakeholder perspective analysis; nexus approach; co-design; transdisciplinary research

1. Introduction

Approximately 80% of wastewater is returned to the environment without prior treatment, severely hampering the health of aquatic ecosystems [1]. Thus, water management is not necessarily considered sustainable. Sustainability intends to simultaneously take into account and provide for the need of "*striving for the maintenance of economic well-being, protection of the environment and prudent use of natural resources, and equitable social progress which recognises the just needs of all individuals, communities, and the environment*" [2]. Achieving sustainability is often referred to as accomplishing the 'triple bottom line' or serving 'People, Prosperity, and Planet'. Sustainable Development intends "[. . .] *to ensure that it [development] meets the needs of the present without compromising the ability of the future generations to meet their own needs*" [3,4]. The 2030 Agenda for Sustainable Development can only be achieved if progress in all 17 goals and more than 230 targets is made in an integrated manner on all three aforementioned fronts of sustainability [5]. Ensuring water security for all stakeholders, including the environment, is also a prerequisite for conflict prevention and resolution.

Achieving water security might, however, come at the expense of food or energy security [6]. To account for the need of balancing those potentially conflicting needs and pressures on resources and services the concept of the Water-Energy-Food (WEF) Nexus

was proposed [7] and has since received much attention in the scientific and development realm. Nexus thinking aims at moving beyond the biophysical, environmental or technical understanding towards political and societal behaviours and needs [8]. Nexus goals can differ but are often connected to an overall aim of advancing towards sustainability and sustainable development [9,10]. Similar to integrated management approaches, nexus thinking is based on holism and systems thinking, necessitates interdisciplinary approaches and intends to foster participation and inclusion of stakeholders in decision-making [9]. Eventually all nexus efforts strive towards better decision-making for an enhanced state of sustainability.

Sustainable wastewater management not only deals with wastewater but often with the impacts of the lack of wastewater treatment on freshwater and aquatic ecosystems or crops and soil ecosystems. Lower-income countries often require support in providing specific equipment or continuous electricity supply for the functioning of aeration systems or pumps of the wastewater treatment systems [11]. They also require highly skilled personnel, often lacking outside of large urban agglomerations [12]. Liang and Yue [13] reported that rural areas, especially, face several challenges to achieve sustainable wastewater treatment, especially struggling with financial sources that cover operation and maintenance costs and dealing with technical constrains regarding proper design and management practices that hamper the proper operation of the wastewater treatment plants. Therefore, currently installed wastewater treatment systems in developing countries do often not perform properly and can be perceived as not sustainable [14,15]. Disciplinary approaches, e.g., from an engineering perspective, are not enough to grasp the difficult challenges of social and political realities, which often hamper a sustainable and sustained solution. Can wastewater systems be described and understood through the nexus lens? And if so, how can the nexus approach or related approaches help in finding solution pathways for sustainable wastewater systems?

While water is part of the 'original' Water-Energy-Food Nexus, considerations of waste(-water) are particularly dominant in the Water-Soil-Waste Nexus [16]. Nexus thinking, in essence, intends to understand interlinkages across resources or sectors that involve biophysical, social, economic and social aspects [17]. A sector considers both the resource and the goods and services that are derived from it. For instance, the Water-Soil-Waste Nexus (WSW) focuses on resources [18], whereas the Water-Energy-Food Nexus (WEF) can be interpreted as focusing on the goods and services provided by these resources [17]. Thus, the water sector comprises the interlinkages and management related to water resources as well as services of supplying water for human use (a good) or collecting and treating wastewater, as shown in Figure 1. Additionally, since the issue of sustainable wastewater management often deals with the impacts of the lack of (adequate) wastewater treatment, interlinkages between wastewater management and water and crop management can be considered as further aspects for assessment. In that sense, seeing wastewater management through a nexus lens can open new perspectives in debates on how to achieve sustainability of wastewater treatment systems going beyond fine-tuning technical equipment of treatment facilities and entering the realm of ecological and social innovations.

While a large effort has been put into 'environmental' sustainability in past decades, with relevant advances, focusing on and achieving gains in the realm of 'social' sustainability seems to be the new frontier. As such, research funding agencies in Europe have been paying great attention to achieving an impact or on-the-ground change. The European Union's Horizon Europe Programme, for instance, monitors its success against nine key performance indicators—three on scientific impact, three on societal impact, and three on technological/economic impact—clearly highlighting the importance of research findings to benefit society and the economy [18]. One way in which these impacts are thought to be achieved is through participatory research approaches such as transdisciplinarity, citizen science methods, or new democratic processes [19,20].
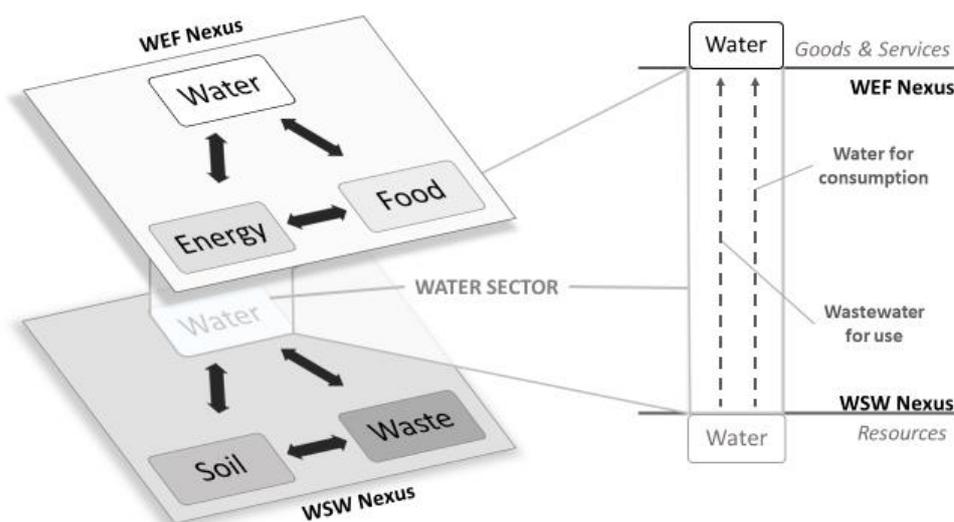
Figure 1. Water in the nexus can be considered a resource for consumption (i.e., for human use) or a sector producing goods and services.

Knowledge production beyond system description is one of the key challenges of sustainability sciences [21]. Transdisciplinary (research) approaches can be considered as useful, even if flawed, ways of obtaining solutions to real-world problems [21]. Albrecht, Crootof, and Scott [22] in their assessment of nexus tools and methods call for more conscious stakeholder integration in nexus projects and the use of transdisciplinarity. Jacobi et al. [23] call for the inclusion of non-academic actors from the project design stage onwards to achieve meaningful knowledge generation and impact in sustainable development. Transdisciplinary approaches inherently go beyond the knowledge of one discipline and set a focus on different modes of perception and valuation by stakeholders, including those of researchers [24]. Brandt et al. [21], based on ProClim [25], refer to three levels of knowledge to be generated by and through stakeholders: "*(i) "system knowledge" the observation of the system, (ii) "target knowledge" the knowledge of the desired target state, and (iii) "transformation knowledge" the knowledge necessary for fostering transformation processes*".

To move beyond system knowledge, nexus thinking must make conscious and consistent use of transdisciplinarity as a concept and utilize its methodological toolbox for effective knowledge generation. Integrating and comparing findings from different disciplinary backgrounds are, however, challenging and make it difficult to provide cohesive recommendations to stakeholders [24]. To date, nexus research has not made use of these levels of knowledge generation, differentiated nexus findings into them or used this approach as a means of cohesively analysing findings from types of analysis of different disciplinary backgrounds.

Based on the premises that (a) wastewater treatment can be considered a nexus problem, and (b) nexus issues need to be tackled through transdisciplinary types of analysis (the authors use the term 'types of analysis' throughout the text as an overarching, interdisciplinary term for methods, tools, and methodologies which, to different disciplines, have different meanings and may lead to confusion), we postulate that (i) knowledge from those analyses can be generated on all three of the aforementioned levels of knowledge; (ii) the approach of using levels of knowledge allows for collating research findings from different backgrounds, and (iii) collating those different knowledges provides pathways for systemic change towards sustainable wastewater treatment systems.

The goal of this article is to develop and exemplify a framework for categorizing results obtained from transdisciplinary types of analysis into the three levels of knowledge for two treatment plants in the Americas. The current analysis used a wickedness analysis, a stakeholder perspective analysis, and a sustainability assessment. These types of analysis intend to represent various disciplinary backgrounds. This article does not focus on the

in-depth description of the methods of the types of analysis (these are described elsewhere and referenced accordingly (see also Materials and Methods section), but rather on the activities and respective results of these relevant to the levels of knowledge generation.

The article first briefly describes the project background and the methods of the types of analysis used while focusing on how the different kinds of knowledge were generated. It then proceeds in presenting the kinds of knowledge generated for each level of knowledge and each type of analysis individually before collating the generated knowledge and deriving overarching pathways towards sustainable wastewater treatment for the cases.

2. Materials and Methods

2.1. Background

This research was carried out in the frame of the SludgeTec project, a multinational partnership between the United Nations University's Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), the Universidad de San Carlos de Guatemala (USAC), the Mexican Trust Fideicomiso de Infraestructura Ambiental de los Valles de Hidalgo (FIAVHI) in Tepeji, Mexico, and the Technische Universität Dresden (TUD). The project aimed for international experts and local stakeholders to co-design solution options for sustainable wastewater treatment and management. The project ran from November 2017 to February 2019.

The project team aimed to determine sustainable pathways for wastewater treatment in two treatment plants in Latin America: Los Cebollales in Panajachel, Guatemala and Tlaxinacalpan in Tepeji del Rio, Mexico. The pilot cases were chosen based on the needs and knowledge of the local project partners. The systems are very different in terms of technologies applied, size, operation, and local contexts, but are similar in the fact that their level of sustainability had not been assessed and was suspected to be poor. A brief description of each treatment plant can be found below for context; more in-depth descriptions can be found in [26].

Pilot Case 1: Panajachel, Guatemala. Los Cebollales is one of the two installed wastewater treatment plants in the municipality of Panajachel and treats 70% of the municipal wastewater. The city has little industry, but high affluence of tourists. The treatment comprises an activated sludge system with a design capacity of 37 litres per second. It was installed in 2012 and commenced operation in April 2013. One of the most crucial challenges is its poor performance regarding the removal of pathogens and nutrients. This is an urgent issue as the plant discharges into surface water bodies of economic, ecological, and touristic relevance (San Francisco River and Lake Atitlan).

Pilot Case 2: Tepeji del Río, Mexico. The Tlaxinacalpan plant in Tepeji is composed of anaerobic biodigesters and constructed wetlands. It was installed in 2017 and commenced operation in February 2018. While the treatment plant was designed for a flow of 1.2 litres per second it was operating between 0.1 and 0.3 litres per second at the time of the assessment. The final effluent is reused for irrigation of the neighbouring soccer field. The Fideicomiso Infraestructura Ambiental de los Valles de Hidalgo Mexico (FIAVHI) has set up 14 such decentralised wastewater treatment plants (WWTP) in the past few years in the community of Tepeji del Río.

Three types of analyses were applied in both cases, namely: wickedness analysis, stakeholder perspective analysis, sustainability assessment.

Understanding the complexity or wickedness of real-world problems can help formulate strategies to address these problems more effectively [27,28]. This research unpacked the wickedness of a problem along the dimensions of (i) goal conflicts related to the problem area; (ii) system complexity, referring to the number of dynamic and interconnected factors, and (iii) informational uncertainty regarding these factors [27]. This helped define generic policy targets for addressing these wicked problems and derive governance recommendations for achieving these policy targets.

While most nexus research systematically calls for participation little guidance is provided about how to determine stakeholders and their relevance in the causes of the

issues at hand or in their role to overcome these [9]. This work used a step-wise approach to understanding "who's in and why" to get an overview of the stakeholder landscape and to provide a notion about their respective role towards the research question and amongst each other [29]. This was accompanied by assessments to understand the stakeholders' desire for their degree of involvement as well as their perception of the changes of their level of knowledge.

When analysing the sustainability of a system, aspects relating to the environment, the economic, the social and the institutional context need to be taken into account [30,31]. Assessments to determine the degree of sustainability of a current or future system are widespread and highly diverse [32–34]. Methods to carry out these assessments range from Life-Cycle Assessments to multi-criteria analyses [35,36]. However, sustainability assessment for wastewater treatment and management are rare and cannot be applied readily to specific cases [37]. Therefore, an iterative process for the construction of an assessment framework prefaced the actual sustainability assessment with an emphasis on including the views of stakeholders. The result was a multi-scalar, multi-dimensional assessment framework through which the degree of sustainability of a wastewater treatment plan was determined using a distance to target approach.

While the wickedness analysis supports the determination of the complexity of the problem at hand, the stakeholder perspective analysis helps better understand the stakeholder landscape as well as perspectives on ideal conditions and how to achieve them. The sustainability assessment provides a snapshot view of the current sustainability of the wastewater treatments system and can help identify aspects that may need immediate fixing. All types of analysis contain both quantitative as well as qualitative results.

These types of analysis were chosen based on the expertise of the research team and because they represent various disciplinary backgrounds. Certainly, other similar types of analysis that provide a combination of system, target and transformation knowledge on social, economic and environmental aspects of wastewater treatment systems can be used. Brief and succinct descriptions of the respective types of analysis are provided in the results section where the relevant activities and their results for knowledge generation are presented. In that sense, the methods of these types of analysis are not methods for the sake of this article but results. A comprehensive and detailed description of the methods for each type of analysis and their related case-study specific results can be found in Avellán et al. [26], Benavides et al. [37] and Kirschke et al. [38]. In addition, a thorough description of conducting wickedness analyses in water-related contexts can be found in Kirschke et al. [27].

2.2. Knowledge Generation Framework

Sustainability sciences, including Nexus research, aim to achieve change through knowledge generation. How knowledge is obtained is diverse, but three levels of knowledge should come together to achieve meaningful transformation: (i) system knowledge, (ii) target knowledge, and (iii) transformation knowledge [21]. As such, 'system knowledge' lays the foundation about the current characteristics of the system including biophysical, social, economic, governance and other aspects. System knowledge defines the status quo. Target knowledge collates the stakeholders' visions of future states. The pendant in modelling is often considered as scenario building. In the context of transdisciplinarity, this includes the individual, organizational and institutional abilities and constraints that may facilitate or hamper the achievement of the desired target; it defines the plausible futures. Transformation knowledge describes the possible pathways to go from the current system to one (or more) desired future(s). These pathways allow for the transformation of behaviours, norms and values, practices and habits that are needed to arrive at the new system, i.e., to obtain systemic change.

As nexus research is embedded in sustainability sciences, the suggestion is to borrow an approach from sustainability science of portraying gained results through levels of knowledge generation. The expectation here is to provide a framework in which to

cohesively represent findings no matter their disciplinary background. In this article, the aim is to extract knowledge across (a) each level of knowledge (system, target, transformation) and (b) for each type of analysis (here namely wickedness analysis, stakeholder perspective analysis, sustainability assessment) (see Figure 2). To achieve this, we propose the following steps:

(1) From the applied types of analysis, we selected activities (e.g., workshop sections, surveys, numeric assessments) that are pertinent to the respective knowledge generation through an inductive approach and assigned their specific results to the appropriate knowledge level (see Table 1). A number of these activities are based on previously developed and applied methods and thus provide a high degree of replicability, e.g., available questionnaires, surveys, or assessments, which are conducive to the use of others.

(2) Based on the results of the activities, we determined the kind of knowledge that was generated for each type of analysis individually, producing a total of nine knowledge items. These provide information about solution pathways from the perspective of each of the types of analysis.

(3) We then collated those knowledge items for each level of knowledge looking for similarities and differences to derive overarching knowledge across all levels of knowledge and types of analyses. This combined knowledge provides information about solution pathways that all types of analysis have in common (reinforcing) or that may have different temporal or spatial dimensions between them (short-term vs. long-term).
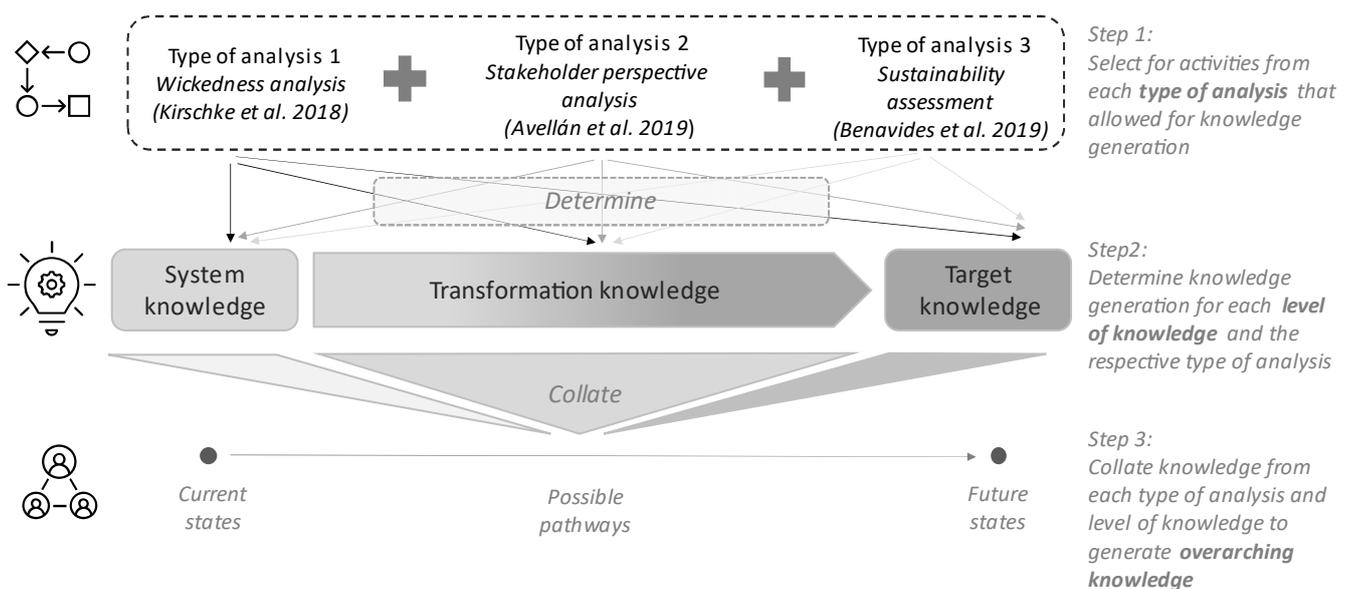

Figure 2. Each level of generated knowledge (system, target, and transformation) was assessed for each type of analysis (namely, sustainability assessment, stakeholder perspective analysis, wickedness analysis) individually and collectively resulting in possible transformation pathways.

3. Results

3.1. Step 1: Selecting for Activities for Knowledge Generation from Each Type of Analysis

Table 1 provides an overview of the selected activities (methods of the types of analysis) used to generate the different levels of knowledge (system, target and transformation) for each of the types of analyses applied in the cases as well as the respective result that was then used to determine if knowledge generation had occurred and, when possible, in which regard. The subsequent sections briefly describe these activities for each type of analysis in more detail.

Table 1. Overview of the activities used to generate different knowledge levels for each type of analysis and the respective result that was analysed to determine the knowledge generated.

Knowledge Level / Type of Analysis	Wickedness Analysis (Kirschke et al. 2018 & Kirschke et al. 2022)	Stakeholder Perspective Analysis (Avellán et al. 2019)	Sustainability Assessment (Benavides et al. 2019)
System (Current states)	Activity: Three roundtable discussions using standardized questions with workshop participants at each pilot site. Result: Degree of wickedness describing the problem.	Activity: Deskwork-based stakeholder identification and broad characterization. Result: Overview of the current stakeholder landscape.	Activity: Assessing which variables of the initial dataset were usable (and why) and sustainability assessment of each of the treatment systems. Result: Use(fulness) of data and degree of sustainability of each of the wastewater treatment systems.
Target (Future states)	Activity: Literature analysis and three roundtable discussions using standardized questions with workshop participants at each pilot site. Result: Policy type which is derived from the problem description.	Activity: Stakeholders' drawings of ideal states at workshops and expert surveys at each case study. Result: Ideal technical-environmental conditions and also political and social interactions & stakeholders that can drive change.	Activity: Obtaining target values for the sustainability assessment based on literature and measurements at each site. Result: Target values for the used indicators.
Transformation (Possible pathways)	Activity: Literature analysis and three roundtable discussions using standardized questions with workshop participants at each pilot site. Result: Stakeholders' suggestions towards changes of policies and policy process.	Activity: Assessing the stakeholders' perception of uptake of knowledge after each of the five stakeholder workshops. Result: Results of the workshop evaluation.	Activity: Scrutinizing the detailed results of the sustainability assessment ex-post. Result: Identification of parts of the system that worked vs. those that did not.

3.1.1. Determining Wickedness

To gather information on the degree of wickedness, we conducted three roundtable discussions with workshop participants at each pilot site, in the assessment workshop in Tepeji in March 2017 [39] and in Panajachel in March 2018 [40]. Each roundtable addressed one of the dimensions of wickedness (goal conflicts, system complexity, and uncertainty). The roundtable discussions were moderated, and guided by a tested wickedness questionnaire comprising three questions per dimension of wickedness, namely goal conflicts, system complexity, informational uncertainty (see Questionaire SM2 or see Supplementary Materials Annex 1 in [27] for an in-depth questionnaire). Results were reported at the workshops and further summarized and evaluated based on contrasting workshop results with methodologies to identify degrees of wickedness based on this questionnaire (Kirschke et al., 2018, Supplementary Material Annex 2). The results of the wicked problem description served as a starting point to define policy targets and governance strategies to reduce distance to target based on literature in the field of wicked problems and the associated stakeholder analysis.

System knowledge for this type of analysis was gathered from the degree of wickedness determined by the stakeholders. Target knowledge was based on the problem description provided by the stakeholders and derived from the literature. Transformation knowledge was derived from actors' suggestions towards changes, in particular with respect to actual policy content, but also regarding process towards policies.

3.1.2. Understanding Stakeholders' Perspectives

The project heavily relied on stakeholder knowledge. To this end, five multi-stakeholder workshops (two opening, two closing, one technical) were carried out. The proceedings of each workshop provide an overview of the activities that were carried out.

(a) Two opening workshops: "Wastewater irrigation in the Mezquital Valley, Mexico: Solving a century-old problem with the Nexus Approach" in Tepeji, Mexico, from 15–17 March 2017 [39] and "Sustainability of wastewater systems: current and future perspectives—an assessment workshop" in Panajachel, Guatemala, from 20–23 March 2018 [40]. Through drawing sessions and structured group work, stakeholders described and analysed the several layers of the problem(s) induced by (un-)sustainable wastewater treatment and management systems, as well as their vision of an ideal, sustainable situation including the actors that might be relevant for this (system and target knowledge). Multiple round-table discussions with different foci on each of the three types of analyses were conducted. The emphasis was laid on fostering a common understanding of the problem across all participants, including the multinational research team, and to delineate the current state and the desired future target state(s) (target knowledge). Workshop activities and structure are described in detail in the workshop proceedings [41,42].

(b) Two closing workshops: "Sustainability of Wastewater Systems" in Tepeji, Mexico, from 12–16 November 2018 [41] and "Sustainability of Wastewater Systems—Presentation of Options" in Panajachel, Guatemala, from 2–4 July 2019 [42]. At these workshops, the results of the research approach were presented to, and discussed with, the respective local stakeholder groups. The main aim was to provide a common understanding of the problem about the missing interlinkages and interconnections in the biophysical resource flow as well as in the information and interactions between stakeholders or stakeholder groups (system vs target knowledge), and to discuss and determine avenues of how to close those gaps (transformation knowledge).

(c) A training workshop focusing on advancing the technical capacities to maintain and operate wastewater treatment plants was offered in Tepeji, Mexico from 13–18 August 2018 (Training on "Basic Knowledge for the Operation and Maintenance of Wastewater Treatment Plants" 13–17 August 2018, Tepeji, Mexico). A specialized trainer from the Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V. (DWA) held this training for 11 participants, mostly from Mexico.

To generate system knowledge, stakeholder identification was carried out in both pilot sites through deskwork and on-site snowballing. Stakeholders were classified using analytical categorization (top-down) where categories were defined by the researchers. This stakeholder identification and categorization provided an overview of the current stakeholder landscape.

To produce target knowledge, various methods were used. An expert interview was set up to assess the stakeholder's perspective about the wastewater treatment plant (Questionnaire in SM1). In total 17 interviews were carried out, 10 in Panajachel and 7 in Tepeji. Expert interviews were carried out in person in Spanish in July/August 2018 and entailed closed questions on a scale from 1 to 4 (1 = low; 4 = high). Results were averaged by site. Moreover, drawing sessions of the initial workshops in each case study location offered insights into ideal technical-environmental conditions, as well as political and social interactions. Participants were asked, in three superimposable layers of transparent paper, to (a) draw an image of the current state, (b) provide ideas about possible changes and (c) indicate stakeholders that would be relevant in achieving sustainable conditions.

To validate whether it was possible to generate transformational knowledge, the project activities were continuously evaluated. To this end, the results of the evaluation of the five multi-stakeholder workshops were analysed. A survey consisting of roughly a dozen questions were handed out to the workshop participants at the end of each workshop (each survey contained a sub-set of questions that was specific to the workshop content and others that were asked consistently across all workshops; Questions and Answers in SM4). The questions were scaled, with 1 presenting the lowest satisfaction and 5 being the highest. The answers were systematized, and the quantitative data was analysed by using the average value of 2.5.

3.1.3. Assessing Sustainability

An extensive exercise of designing and setting up a framework of relevant data for a sustainability assessment of wastewater treatment systems on multiple scales was carried out. This resulted in an extended dataset framework of roughly 500 variables distributed along four dimensions (context data, technical-environmental data, social-economic data and multiscalar-social data) and on four levels (plant, municipality, sub-catchment, catchment; see the full extended dataset framework in Annex 1 of [26] or SM1 of [37]). The multi-scalar systems were defined as suggested by Avellán et al. [43] while being conscious that these may not take all social system boundaries into account. Site-specific data sets were created through a set of criteria including stakeholders' opinions. These criteria were: (1) stakeholders choose the variable during one of the workshops, and the literature on wastewater management confirms its relevance, (2) locally applicable regulations call for the variable. The sustainability assessment was performed on a subset of those variables of the site-specific dataset which presented both a value for the current situation (e.g., pH of effluent water) as well as a threshold value to compare it to (e.g., stipulated pH threshold value as per local/national/international norm).

The sustainability assessment looked at the degree of sustainability across, but also within, each of the dimensions of sustainability, namely, technical, environmental, economic, and social. For this, the project team used a simple traffic-light system that evaluated the distance from a set threshold to the actual variable value following Bertanza et al. [44]. A categorisation of 'red' clearly indicated that the treatment system was failing to be sustainable in that particular variable and dimension, while a 'green' showed compliance, and a 'yellow' indicated an intermediate state where improvements are needed.

System knowledge was derived on the one hand from the use (fulness) of data and, on the other hand, from the actual result of the sustainability assessment, i.e., the degree of sustainability of each of the wastewater treatment systems. Target knowledge was assessed through the determination of target values for the used indicators. Transformation knowledge was determined by analysing the parts of the system that worked (high measures of the sustainability i.e., 'green') and those that did not (i.e., 'red') and deriving recommendations for change.

3.2. Step 2: Generating Knowledge for Each Type of Level and Each Type of Analysis

In general, the problem at the pilot site in Guatemala revolved largely around **sustainable wastewater management**, concerning the resources of water and waste and the sectors of water and recreation/tourism. The resources were interlinked through the negative impact of the insufficient treatment system on surface water quality of the receiving river and lake. The sectors were interlinked through the impact of insufficient treatment on drinking water quality and of polluted receiving water on bathing water quality and its general appearance for recreational purposes (e.g., algal blooms).

In Mexico the problem was defined more specifically on the **safe use of wastewater in agriculture** since the wastewater treatment system was designed for reuse purposes. The interlinked resources were water, soil and waste, as the application of insufficiently treated wastewater can have negative impacts on soil health but also on surface and sub-surface water. The sectors involved related to water, agriculture and health, as the farm workers can fall sick from poorly treated wastewater for irrigation purposes when handling crops or produce. Similarly, the soil health can be negatively affected by salinization and heavy metal accumulation which, in turn, affects agricultural production.

3.2.1. System Knowledge

The current state of the system was characterized by a high degree of wickedness, a diverse stakeholder landscape, and an uneven distribution of the number of variables across dimensions and scales for sustainability assessment, with a low to medium degree of sustainability.

The results of the roundtable discussions at the workshop on **wickedness** showed that in both cases the current system view of the problem is highly wicked based on mostly high levels of wickedness in each of the three dimensions (goal conflicts, system complexity, informational uncertainty; see Table 2 and respective questions in Questionaire SM2). Aspects of diverging interests of stakeholders, a high number of dynamic and interconnected social and natural aspects, and a lack of data and information (sharing) strongly influence the wickedness of the problem. The respective arguments are driven by internal (e.g., local information flows) and external factors (e.g., climate change or an increasing number of tourists). While both cases show similar patterns, Panajachel shows stronger information deficits, emphasizing limited sharing or use of given information.

Table 2. Degree of wickedness in each of the three dimensions of wickedness in each case with brief descriptions of what constitutes the degree (based on Workshop Report 1 [39] and 2 [40]).

Dimensions of Wickedness	Panajachel	Tepeji
Goal conflicts	High There is a joint interest in achieving good freshwater quality. However, there are conflicts on a social, economic, technical, and institutional level that hinder the achievement of good water quality, including disagreement of the population with the use of treated wastewater, limited capacity to pay for treatment technologies, a lack of skilled personnel, and low coordination leading to a duplication of functions of individual institutions.	High Actors share common interests when it comes to the prioritisation of economic aspects. However, there also exist conflicts of interest as some actors are interested in the reuse of wastewater whereas others have concerns about reusing wastewater, such as for the irrigation of crops. Concerns are mostly put forward by farmers, consumers, and the health sector, emphasizing a lack of trust, limited knowledge, and particular concerns regarding the possibility of epidemics.
System Complexity	High The problem is influenced by many factors, amongst them natural factors (e.g., the specific topography, climate) and social factors (e.g., responsibilities of governments, the level of education, interests of indigenous communities, associations, tourist organisations, and three governmental levels). Factors influencing the solution to the problem are also subject to dynamic processes such as changing temperature, demographic development and related social and political conditions, and an increasing number of tourists in the region. These factors are also highly interconnected, e.g., as political decisions influence the number or demographic developments or tourism on site.	High The problem is influenced by a large number of factors such as the many actors involved, their different educational backgrounds and interests, the management of wastewater reuse practices, geographical location, the lack of alternative options for the use of untreated wastewater, and framework conditions. Factors influencing the application of safe wastewater reuse in agriculture are also subject to dynamic processes, such as population growth and the quick turnover of politicians. Further, interconnections between factors (e.g., between crop type, irrigation techniques, and ownership of land) hinder changes in agricultural practices or policies.
Informational Uncertainty	High While there are data and information at hand, they are sometimes dispersed across different institutions. Moreover, information on natural and social factors are lacking, including the quantity and quality of water, precipitation, temperature, soil types and topography, existing forests, the number of inhabitants and future demographic developments, evaluations of economic, social, and environmental benefits, and typical uses of water, operational instructions, among others. Obtaining data and information is hindered by lack of planning capacities, methodologies, and the willingness to collect and share information.	Medium There is a certain lack of information on the part of both government and local communities, e.g., in terms of social benefits, wastewater outflow quality, the benefits of wastewater treatment, and costs. However, the case is mainly defined by limited sharing of information, e.g., with respect to the risks connected to untreated wastewater practices and safe reuse of treated wastewater in agriculture in respective studies. At the same time, the available information is not used by the relevant actors due to language issues or lacking specificity. Nevertheless, it appears that the dissemination of relevant information among stakeholders seems to be feasible through relevant governmental offices, among local experts, and official documents.

To understand the system from a **stakeholder perspective**, stakeholder identification and rough stakeholder characterization were used. In the case of Panajachel, 62 stakeholders were identified and clustered in 13 stakeholder groups. A similar but much smaller stakeholder landscape resulted for Tepeji, where 17 stakeholders and 10 stakeholder groups were identified (see Table 3). Stakeholder groups were, for instance, the municipality, wastewater treatment plant operators and managers, non-governmental associations and

community groups, or local, national or regional decision-making entities (see [26] for a more detailed overview of stakeholders). For the Guatemalan case, prominent stakeholder groups were highly local including the municipality, national decision makers, community associations/NGOs/community representatives, and other non-classified stakeholders. For the Mexican case, the municipality played a major role, followed by stakeholders of the wastewater treatment system (managers and operators) and the local community and their representatives.

Table 3. Overview of the number of stakeholders and stakeholder categories for each of the cases.

	Panajachel	Tepeji
Number of stakeholders	62	17
Number of stakeholder categories	13	10

In terms of system knowledge, the sustainability assessment provided two kinds of information (a) data availability, and (b) the state of sustainability of the systems. Data availability was an issue. Out of the ~500 variables in the extended data framework 218 site-specific variables were pre-selected through desk work and stakeholder consultations for Panajachel, and 195 for Tepeji (see Table 4). While data may have been selected as important by stakeholders and/or the literature, not all data items were actually available or found when seeking them (e.g., water quality data of plastic pollution was deemed as important, but no testing had been done so no data were available). In addition, for data to be used for the evaluation, threshold values to compare field data had to be available (e.g., from national or local norms or decrees on water quality).

Table 4. System knowledge. Overview of data items selected, found and used (based on Tables 4–7 of [37]. Only variables from the wastewater treatment plant (WWTP) scale were considered for further assessment (grey shaded areas); * context information was not used for the sustainability assessment.

Subset	Description	Scales		Extended Dataset Framework	Number of Data Items Selected		Number of Data Items Found		Number of Data Items Used	
					Panajachel	Tepeji	Panajachel	Tepeji	Panajachel	Tepeji
Dataset 0—Context indicators	Understanding of context: geographical location and characteristics, poverty, and employment indicators	1	WWTP	7	1	3			*	*
		2	Municipal	18	0	3				
		3	Subcatchment	13	0	4				
		4	Watershed	12	0	5				
		Total		50	1	15	1	10	-	-
Data set I—Technical—Environmental.	Technical and environmental variables (e.g., population served, chemical parameters of water bodies and of effluents, WWTP management)	1	WWTP	211	98	107				
		2	Municipal	31	15	15				
		3	Subcatchment	70	55	15				
		4	Watershed	68	18	18				
		Total		380	186	155	88	93	52	48
Dataset II—Socio—Economical	Economic, financial, budget variables. Dataset IIb useful to understand the social acceptance of the system	1	WWTP	16	8	7				
		2	Municipal	17	8	5				
		3	Subcatchment	7	0	0				
		4	Watershed	12	5	3				
		Social space (cross-scale)		10	10	10				
		Total		62	31	25	23	18	10	7
		Overall Total		492	218	195	112	121	62	55

The complex set-up of multiple scales on the one hand (wastewater treatment plant, municipal, sub-catchment, municipal), and several dimensions of sustainability on the other hand (technical-environmental and socio-economic) proved challenging to comply with. As such, the technical-environmental dataset contained the highest number of variables selected, found and used, resulting in roughly five times more variables used here versus those from the socio-economic dataset. In terms of scales, that of the treatment plant claimed the highest number of variables and was the one pursued further for the assessment. For the sustainability assessment, 51% of the site-specific variables could be used for Panajachel, and 62% for Tepeji. While it may appear disheartening that such few data could be found and used, co-created system knowledge about available data, threshold values and missing

information now exists in the form of site-specific data sets for each case (see Appendix A and B of [37] for the site-specific data sets and Appendix F and G of [37] for the data values of the indicators used in the sustainability assessment).

As for the level of sustainability, neither of the systems was fully sustainable. In Panajachel, the score was roughly above the lowest limit (red category), implying an overall low to medium sustainability (see Table 5). In Tepeji, a medium to good performance in the available dimensions was observed. However, the sustainability assessment is incomplete as the economic dimension could not be evaluated due to missing data.

Table 5. System and Target knowledge. Sustainability assessment results using a distance-to-target approach for Panajachel and Tepeji. Adapted from Benavides et al. [37].

Dimension	Dimension Average *			
	Panajachel		Tepeji	
	Value	Level	Value	Level
Technical-Environmental (TE)	−0.08	Y	0.38	G
Economic (Ec)	−1.00	R	ND	ND
Social (S)	0.29	Y	0.14	Y
Average	**−0.26**	**Y**	**ND**	**ND**

* Following Bertanza et al. [44]. R: Red; Y: Yellow; G: Green; ND: No Data.

3.2.2. Target Knowledge

How to set target values or determine good target state differs according to the type of analysis employed. Keeping this in mind can be critical for cross-disciplinary understanding amongst researchers, the transfer of the results to stakeholders, and the discussion and implications of these results with them.

The **wickedness analysis** showed that reducing high degrees of goal conflict, system complexity and information uncertainty would be the target state at policy level. The **stakeholder perspective analysis** indicated the target state was the empowerment to co-decide. For the **sustainability assessment** a fully sustainable treatment system was the overall target state, i.e., a high degree of sustainability (green) in all three dimensions.

The **wickedness analysis** derived targets for addressing wicked problems based on the problem descriptions provided by the stakeholders (Table 6). Targets refer here to the design and implementation of policies aimed at the resolution of problems along the three dimensions of wickedness. For goal conflicts, both cases target coherence through the resolution of conflicting interests between different stakeholders [45]. Addressing system complexity aims at delivering comprehensive policies that take into the account the complexity of social-ecological systems [46]. Information uncertainty traditionally calls for adaptable policies and special mechanisms for regulating data collection and sharing [47]. While both cases show similar targets, the respective policies should consider the specificities of the pilot cases.

Setting target states across different stakeholder groups is important to obtain clarity of direction. The target state to be achieved through the project was that of a sustainable wastewater treatment and management system. In the context of the **stakeholder perspective analysis**, visioning exercises in the assessment workshops [39,40] (e.g., through drawings) allowed the stakeholders to describe their desired technical-environmental target states. These ranged from safe use of wastewater in agriculture, to reduced pollution loads of the receiving waters, to inclusive and participatory solid and liquid waste management.

The drawings also provided information about the stakeholders' perspectives about (a) which stakeholders are relevant to the issues at hand, and (b) how these stakeholders should interact with each other. Figure 3 shows examples of drawings from Panajachel featuring both public entities and citizens as relevant stakeholders.

Table 6. Policy characteristics for addressing the three dimensions of wickedness.

Dimensions of Wickedness	Panajachel	Tepeji
Goal conflicts	Design and implement coherent policies that improve freshwater quality, while (i) making limited use of treated wastewater or (ii) accompanying its use with trust-building measures, financial mechanisms to increase the population's capacity to pay for treatment technologies, financial support for addressing a lack of skilled personnel, and improved coordination amongst institutions	Design and implement coherent policies that improve the economic dimensions of sustainability while (i) limiting the reuse of wastewater or (ii) addressing concerns about the reuse of wastewater through trust-building measures, information campaigns, explicitly including measures against epidemics.
System Complexity	Design and implement comprehensive policies that take the features of dynamic complex social-ecological systems into account, with special emphasis on the multitude of natural and social factors specific to the region, such as dynamics of tourism and demographic developments.	Design and implement comprehensive policies that take the features of dynamic complex social-ecological systems into account, with special emphasis on the multitude of natural and social factors specific to the problem, such as the crop type, irrigation techniques, and land ownership.
Informational Uncertainty	Design and implement policies that include adaptation mechanisms to account for new data and information at hand, that (i) increase the capacity of institutions to collect data and information, and (ii) regulate or set incentives for information flows between key institutions.	Design and implement policies that (i) regulate or incentivise information flows between different institutions and stakeholders including associated risks and an appropriate level of language and specificity, and (ii) that can be adapted in case of new information.

Figure 3. Example of drawings from stakeholders of the treatment plant in Panajachel depicting their perception of the issue and potential actors that could help achieve a more sustainable situation.

The answers to the questionnaire (see Questions in SM1) indicate the perception of stakeholders about their view on how stakeholders should, or could, be involved in solving the issues (Table 7 full list of responses in Questionaire SM3). In general, awareness of the problem and the degree of participation was perceived to be higher and more favourable in Panajachel (4 and 3.6, resp. out of a max. of 4) than in Tepeji (3.6 and 3.3, resp.). Social acceptance was very low in both cases, but particularly low in Panajachel (1.2 vs. 2.6 in Tepeji). Respondents of both cases were highly interested in being part of the decision-making process (4.0 and 3.9 resp.) but felt that their recommendations had only obtained medium attention (2.2 and 3.0 resp.), decision-making was not always being done in a co-design manner (3.2 and 3.1 resp.) and publicly available information was perceived as low (2.4 and 1.9 resp.). Increased social acceptance can be considered a desired target state by the stakeholders, which could be achieved through increased participation in decision-making processes. These, seemingly, should follow a co-design approach, providing avenues to stakeholders to obtain the relevant information and provide recommendations.

Table 7. Summary information about the mean scores of the responses to the survey questions about the awareness, perception, and social acceptance of the issues.

	Panajachel * (*n* = 10)	Tepeji * (*n* = 7)
1. Awareness of the problem		
1.1. How interested are you in the problems related to wastewater management in your region?	4.0	3.7
1.2. How aware are you of the problems related to wastewater management in your region?	4.0	3.6
2. Participation		
2.1. Information sharing		
2.1.1. How often have you tried to access certain information regarding problems related to waste water management in your region?	3.6	3.3
2.1.2. How much information is publicly available on wastewater management problems in your region?	2.4	1.9
2.2. Recommendation		
2.2.1. How many possibilities are there to give recommendations regarding wastewater management problems in your region?	3.4	2.7
2.2.2. Have your recommendations been taking into consideration?	2.2	3.0
2.3. Decision-making		
2.3.1. How interested have you been in being part of the decision-making process?	4.0	3.9
2.3.2. To what extent have decisions been taken in a co-decision-making process regarding wastewater management problems in your region?	3.2	3.1
3. Social Acceptance		
3.1. How satisfied are you with the current wastewater management in your region?	1.2	2.6
3.2. How satisfied are the citizens with the wastewater management in the region?	1.3	1.6

* Mean score (1 = low; 4 = high).

For the **sustainability assessment**, defining target states for the variables is crucial. Although a qualitative change was sometimes possible (e.g., increase/decrease), obtaining an actual (numerical) data value for each site-specific variable was not. Data quality, the lack of applicable standards, and thresholds reduced the number of variables with which a sustainability assessment could be performed (see Table 4). The lack of data led to abandoning the multi-scalar approach by focusing mostly on variables for the scale of the wastewater treatment plant. In both cases, a heavy slant towards variables of the technical-

environmental dimension (such as water quality variables) occurred, as data for them was more readily available and with the highest robustness and reliability. Overall, carrying out the sustainability assessment relied on both system and target knowledge. The generation of this knowledge built on the data and information provided by all stakeholders, including their preferences of variables and acceptable thresholds.

3.2.3. Transformation Knowledge

Transformation knowledge allows determination of pathways towards systemic change intending to arrive at a (more) sustainable state. Results here refer to changes in habits (e.g., data collection and information sharing across (more) diverse actor groups), values and norms (e.g., co-decision making of non-political actors is considered important), or behaviours (e.g., acting within their local abilities instead of waiting for external aid). These alterations may not feel intuitive, obvious, clear, or achievable. Such changes are challenging but are intended to be long-lived. They are needed in addition to short-term changes that support immediate relief to the obvious problem, i.e., the technical malfunctioning of the treatment system.

In terms of **wickedness analysis**, the question is how governance can support the design of coherent, comprehensive, and adaptable policies to account for the conflicts, complexities, and uncertainties of the given case. The project team derived general recommendations for actions to address wicked problems, as provided in the literature on wicked problems [48,49] taking into account the suggestions of stakeholders during the workshops (see Table 8). Research mainly focuses on collaborative governance approaches, including the involvement of different types of actors (e.g., scientists, politicians, technicians) and different forms of interactions (e.g., deliberating, negotiating). However, these strategies are intense in time and capacity, and may reduce the capacity for adaptive decision-making. Collaborative governance approaches (and their drawbacks for policymaking and implementation) apply to both cases.

Table 8. Forms of collaborative governance for addressing the three dimensions of wickedness.

Dimensions of Wickedness	Panajachel	Tepeji
Goal conflicts	Collaborative governance approaches to address goal conflicts, including (i) the involvement of the key opponents (here representatives of the population and public authorities) and (ii) negotiations combined with deliberations as a dominant form of interaction.	Collaborative governance approaches to address goal conflicts, including (i) the involvement of the key opponents (here representatives of the proposers of the use of wastewater in agriculture as well as farmers, consumers, and the health sector) and (ii) negotiations combined with deliberations as a dominant form of interaction.
System Complexity	Collaborative governance approaches to address goal conflicts, including (i) the involvement of scientists to model system complexity, and (ii) deliberation as a dominant form of interaction to design and adjust the system according to new knowledge.	Collaborative governance approaches to address goal conflicts, including (i) the involvement of scientists to model system complexity, and (ii) deliberation as a dominant form of interaction to design and adjust the system according to new knowledge.
Informational Uncertainty	Collaborative governance approaches to address goal conflicts, including (i) the involvement of data and information holders from the public, private, and civil society sector and (ii) deliberation as a dominant form of interaction.	Collaborative governance approaches to address goal conflicts, including (i) the involvement of data and information holders from the public, private, and civil society sector, in particular the different institutional information holders, and (ii) deliberation as a dominant form of interaction.

Stakeholder perspective analysis was possible through the project activities (multi-stakeholder workshops and a technical training) which facilitated knowledge generation

between the project team and the local stakeholders, as well as amongst the local stakeholders. The project activities focused on (1) a common understanding of the problem (e.g., quality of the effluent, pollution load on the environment, legal aspects), (2) providing information about potential technical improvements (e.g., other forms of sewage treatment, consequence of wastewater (re-)use) to then (3) jointly developing pathways for solutions that can be implemented. The knowledge generation process was validated based on evaluations of the project activities (see Table 9; full raw data results in Questionaire SM4). The results show that the workshops demonstrated a high satisfaction rate (above 3.9 out of 5) across all types of activities and cases. The satisfaction rate was noticeably high for the technical training highlighting the importance of conveying knowledge about technical improvements.

Table 9. Overview of the results of the evaluation of project activities (WS- Workshop; 1—workshop towards the beginning of the project; 2—workshop towards the end of the project).

Question	WS1 Panajachel (*n* = 14)	WS1 Tepeji (*n* = 14)	WS2 Panajachel (*n* = 39)	WS2 Tepeji (*n* = 17)	Technical Training (*n* = 10)
What is your overall assessment of the workshop?	4.7	4.7	3.9	4.6	4.8
How do you assess the organization of the event?	4.8	4.8	4.0	4.5	4.9
How do you rate the balance of presentations and breakout sessions?	4.6	4.6	3.9	4.5	4.7
How do you rate the quality of the presentations?	4.9	4.6	3.9	4.8	4.9
How do you rate the quality of the breakout/discussion sessions?	4.8	4.5	4.0	4.7	4.7
How do you rate the quality of the interactive sessions?	n/a	n/a	n/a	n/a	4.9
Did the workshop help you in understanding the nexus approach?	4.4	4.7	n/a	4.6	n/a
Did the workshop help you in understanding the sustainability of current solutions?	n/a	n/a	n/a	4.6	n/a
Did the workshop help you in understanding the complexity of the problem?	4.8	4.8	n/a	4.7	n/a
Did the workshop help you in understanding the stakeholder network?	n/a	n/a	n/a	4.8	n/a
Did the workshop help you in identifying sustainable management options for wastewater and sludge?	4.6	4.6	n/a	4.3	4.9
Did the workshop help you in identifying how to implement the identified solutions?	n/a	n/a	n/a	4.2	n/a
Will you be able to use what you have learnt in your work?	4.4	4.8	n/a	4.6	4.8
Did the workshop help you in understanding the various treatment concepts?	n/a	n/a	n/a	n/a	5
Did the workshop help you in understanding the complexity of the operation of several treatments of wastewater in a plant?	n/a	n/a	n/a	n/a	4.9
Did the workshop help you in understanding the monitoring and documentation of the operation?	n/a	n/a	n/a	n/a	4.8
Did the workshop help you in understanding the technologies of small/decentralized plants?	n/a	n/a	n/a	n/a	4.7

Score meaning: 1 = low, 5 = high.

The **sustainability assessment** allowed identification of critical variables that could be addressed. These included enhancing technical capacities of the treatment systems such as inoculating bioreactors or fixing the broken aeration systems to enhance the overall treatment efficiency and thus getting closer to or achieving compliance with local effluent norms. The assessment pointed to the lack of economic variables and thresholds that would allow for a robust assessment of the economic dimension of sustainability. Variables such as per capita cost of wastewater treatment, or proportion of costs: maintenance and repairs, can help judge the economic health of a treatment plant.

3.3. Step 3: Collating Knowledge

The working hypothesis introduced at the beginning of this article focused on three aspects: (a) system knowledge generation, (b) target and transformational knowledge generation, and (c) solution pathways.

All three types of analysis generated **system knowledge**. The sustainability assessment identified and prioritized variables that best describe each of the treatment systems through their level of sustainability. The latter being the focus of the project, this type of analysis provides a centrepiece of knowledge. The stakeholder perspective analysis offered basic but important information about the number and types of stakeholder (groups) critical knowledge to allow for participation. The wickedness analysis portrayed the perceived challenges towards solving the problem. Together, these types of analysis showed that the systems were not sustainable, exhibited high levels of wickedness, would be challenging to find solutions for, and contained diverse stakeholder landscapes that may exhibit different needs. This level of knowledge provides temporary, snapshot-like information—it offers no solutions.

The analysis also generated **target and transformational knowledge**. In fact, for both the sustainability assessment and the stakeholder perspective analysis, target knowledge was critical to determine system knowledge. Only by comparing the current system state with a desired ideal/target state could the assessments become meaningful. Sustainability assessment is dependent on threshold values which are defined by target situations. Obtaining actual values for these thresholds was a challenge and significantly hampered carrying out the sustainability assessment on multiple scales. This confirmed the high degree of wickedness determined in the system knowledge in the dimension of data uncertainty. The methods used to determine the desired targets of stakeholders with respect to their environmental views, and also about whom they would like to see involved and how, were telling. The drawings provided idealized views with less pollution and more pollution control carried out both by political entities and the local citizens. The answers to the questionnaire indicate the desire to be empowered towards decision-making while highlighting the lack of (access to) information relating to the treatment plant and its environmental effects. Coherent policies that set clear pollution thresholds, and also institutional capacities to enforce these, emanate from the sustainability assessment as well as from the results of the wickedness analysis. Therefore, the types of analysis reinforce each other around legal frameworks. Similarly, a lack of data and information, as well as access to these, is highlighted in all three types of analyses. Knowledge exchange amongst stakeholders and provision of (technical) knowledge is critical to establish knowledgeable stakeholders that can make informed decisions that are desired and needed.

The three types of analysis provided **solution pathways** to overcome the non-sustainable situation detected, which mostly stemmed from the information drawn from the transformation knowledge. Each type of analysis individually offered certain recommendations for actions. The results of the sustainability assessment suggest fixing mainly technical aspects of the treatment plants. However, even though these technicalities can temporarily increase the sustainability at a next 'snapshot' assessment, these may not be of long duration. The lack of data in the economic (and to some degree in the social) dimension significantly hampers the ability of this type of analysis to offer long-term, systemic change recommendations. The recommendation here is thus the collection of those data items (as well as

those in the technical-environmental dimension) to be able to gain a better understanding of the effects of those aspects on the sustainability of the system.

The stakeholder perspective analysis indicates the desire for more information in general, and technical information about the treatment system and its performance and environmental effects, in particular. Technical trainings at various levels of depth could enhance capacities of technical personnel in treatment plants or the respective personnel in the municipalities and oversight entities. Awareness-raising campaigns, but also openly accessible data observatories for the general public, could boost basic knowledge of citizens and develop their capacities to intervene. The wickedness analysis recommends interventions of (specific) stakeholder groups to design coherent, comprehensive, and adaptable policies. The stakeholder perspective analysis indicates that viewpoints from citizens or citizen-led groups should not be ignored. Therefore, these two types of analysis define a pathway towards systemic change by increasing the knowledge level of stakeholders on technical aspects around wastewater treatment and its environmental effects to make more informed decisions when designing policies. Conversely these policies can enhance the performance of the sustainability assessment by making more threshold values available, and allow for more and broader monitoring –including citizen-led monitoring and data observatories—making its results more meaningful in the long run.

Overall, system knowledge was created individually, but also collectively, from these three types of analysis, providing a snapshot of the current situation (Table 10). In addition, resulting target and transformation knowledge provided both immediate recommendations to improve the sustainability of each of the treatment systems, but also recommendations for systemic change to improve sustainability in the long run. The interplay between the types of analysis is exciting, as each offers an element for recommendation, but only through the collation of the results can a meaningful long-term recommendation be made.

Table 10. Summary of the main levels of knowledge generated by each type of analysis.

Type of Analysis vs. Knowledge Generated	Wickedness Analysis	Stakeholder Perspective Analysis	Sustainability Assessment	Collated Knowledge by Knowledge Level
System knowledge	High degree of wickedness in all three dimensions	Diverse stakeholder landscape	Lack of data and sustainability of the system	Non-sustainable highly wicked systems with diverse stakeholder landscapes
Target knowledge	Address wicked problems through coherent, comprehensive, and adaptable policies	Allow and provide for the inclusion of stakeholders' views in decision-making processes in a transparent and open manner	Set threshold values to assess sustainability against	Obtain threshold values from policies which have been decided upon through stakeholder involvement
Transformation knowledge	Involvement of specific types of stakeholders, interaction through deliberation (negotiation)	Make use of activities that focus on increasing knowledge about specific aspects such as technical trainings and the exchange of local information and knowledge	Fix case-specific technical aspects, collect more robust (economic) data	Focus on activities that enhance the respective stakeholder's knowledge to allow for more informed decision-making
Collated knowledge by analysis type	The degree of wickedness is high in both cases and across its three dimensions. Wicked problems should be addressed through coherent, comprehensive, and adaptable policies that have been deliberated upon with specific stakeholders.	The stakeholder landscape is diverse, and stakeholders request their views to be included in decision-making processes. For this, they desire more and better information (flows) in general and on technical aspects in particular to be able to better make decisions.	Systems are not sustainable and can be improved by fixing technical aspects. Sustainability assessment itself is faulty due to the lack of (access to) variable and threshold value data. Data collection efforts may be most relevant for economic data values.	Recommendation for immediate improvement of performance of treatment systems—Fix technical issues. Recommendations for systemic change for long-term improvement of the sustainability of treatment systems: - Enhance knowledge of stakeholders through (technical) trainings and multi-stakeholder activities - Establish an expanded database - Empower stakeholders to make informed decisions and to shape policies

4. Discussion

This article presents and exemplifies a framework for extracting and combining knowledge of three transdisciplinary types of analysis. The aim here was to provide a means of integrating results from types of analysis from different disciplinary backgrounds which may offer pathways on the nexus issue of moving towards sustainable wastewater treatment systems. We propose here a three-step process whereby one: (1) selects for activities in each of the types of analysis that generate system, target and transformation knowledge, (2) matches the results from those activities to the knowledge type, and then (3) analyses the knowledge generated for each type of analysis, as well as across them.

These three types of analysis proved that non-model methods can furnish system knowledge and provide information about interlinkages. The underlying conceptual system description for the sustainability assessment as presented in Benavides et al. [37] is very close to system representations such as causal loop diagrams that support the visualization of interlinkages between system elements. The drawings used, mostly to derive target knowledge for the stakeholder perspective analysis, are simplified versions of system representations showing interlinkages not only of the bio-physical aspects but also about the human interactions within these, thus moving towards more comprehensive system representations (e.g., [37,50,51]). In addition, findings suggest that consciously applying transdisciplinary research principles that explicitly target all three areas of knowledge generation are critical to overcome the status of simply describing the system and moving towards solution pathways. In terms of specific results for the particular cases of the two treatment systems assessed here in Mexico and Guatemala, each type of analysis provided system, target, and transformation knowledge. While system knowledge showed a snapshot of the situation, the other two levels of knowledge offered insights into solution pathways towards sustainability. While each type of analysis indicated particular elements of the situation (high degree of wickedness, diverse stakeholder landscape, lack of economic data) as well as for solution pathways (involvement of certain stakeholders, increasing technical knowledge, fixing technical problems), collating the results offered meaningful perspectives highlighting reinforcing elements (e.g., improved information flows, specific targeting of stakeholders for deliberations on policies, focused data collection efforts to strengthen sustainability determination). At the same time, the results also highlighted very different aspects (stakeholders, data, policy process).

While the applied types of analysis used here are certainly no panacea, their use led to effective on-site decision-making. Once presented with the results of the types of analysis, stakeholders decided to act upon the findings by (a) holding their local politicians accountable, (b) launching awareness raising and environmental education campaigns, and (c) organizing follow-up events taking further stakeholders into account. Long-term impact analyses only can show if systemic changes were achieved.

This study also showed that lack of data hinders demonstrating a holistic picture of sustainability, and that considering aspects such as stakeholder perception and how to shape policies in the face of wicked problems, can effectively show longer-term pathways towards systemic change and sustainable solution options. This is key, since a large focus of the nexus research community has been on better understanding interlinkages in bio-physical systems with little social or behavioural information. Numerical model outputs are often hampered by lack of data [22]. It may therefore be advisable to move beyond the improvement of numerical models that focus on increasingly interlinked systems understanding towards the co-production of knowledge with tools that provide information on (1) all three levels of knowledge, (2) within different stakeholder groups—project team, case study stakeholders, others, and (3) making use of diverse data sets (Figure 4).
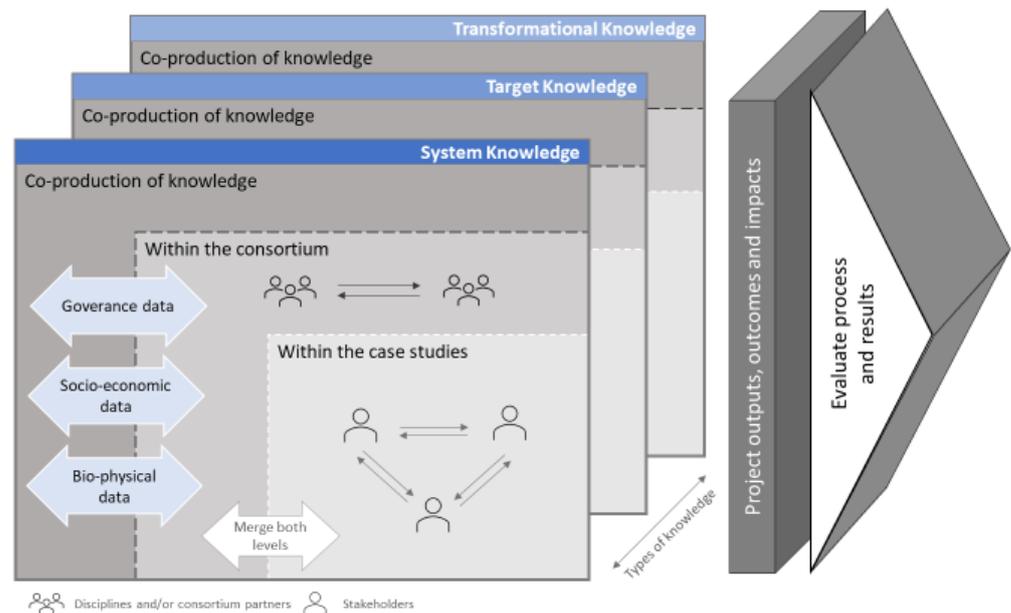
Figure 4. Representation of the different levels of knowledge, and knowledge sharing for collective and comprehensive knowledge generation.

Methodologically, the selection of activities to determine the level of knowledge was carried out ex-post. Nonetheless, this work now provides a set of consistent activities for some of the elements of knowledge generation, such as questionnaires for the generation of all levels of knowledge for wickedness analysis, questions for the generation of transformation knowledge for stakeholder perspectives, and a comprehensive indicator set to choose from for the generation of system knowledge for sustainability assessment (see methods description in Table 1 and the full set of questions of the respective Questionnaires and Surveys in S1–S4). These consolidated methods can be applied in other cases and be developed further and refined.

We are also conscious of the fact that the current selection of types of analysis may not be comprehensive and sufficient to cover all aspects needed to provide the 'right' pathways towards sustainability. Some recommendations when choosing types of analysis for knowledge generation from this work are that:

(1) they be conducive to generate knowledge of all levels—system, target and transformation (i.e., models that only describe the current system may not generate other knowledge types),

(2) a conscious selection and design of activities be carried out with a view to generating one or more knowledge type to be able to extract the findings easily (i.e., setting clear aims), and

(3) the types of analysis be complementary to each other in covering different geographic boundaries and scales, and elements of the human-environment system (i.e., assessing more than the bio-physical interlinkages of resources).

We also see value in collating knowledge in a participatory manner, which we leave here as a recommendation for future projects. Reflecting collectively with the stakeholders on the individual finding of each type of analysis and considering overlaps and differences as a group might have unearthed further aspects or provided different insights. We also acknowledge that we did not follow a systematic process to collate the knowledge other than logically linking the outputs of the three analyses. Future work could focus on developing structured steps to collate knowledge (e.g., use of same terms in the concluding remarks of each analysis, looking for causality, verification of drivers across the three analyses). Overall, this work does provides a structured approach of extracting generated

knowledge from activities of any applied type of analysis and collating this to provide pathways for systemic change.

5. Conclusions

Wastewater treatment systems, when designed and operated in a sustainable manner, can be pathways for sustainability. By reducing pollution loads and providing for resource reuse (be it water for irrigation, energy production from biogas or direct combustion, soil amendments from sludge and other solid organic bio-products) wastewater treatment systems can be useful elements of sustainable development [52,53]. For this paradigm shift from a linear input-output system to a sustainable circular system to happen, we must start viewing wastewater treatment plants as systems that are not solely technical but as systems that embed themselves in the human-environment system [54]. To be able to comprehend the elements that this new, broader system view of wastewater treatment systems entails other, more comprehensive and non-technical types of analysis.

Using nexus thinking to address wastewater treatment systems offers a more holistic view and suggests using types of analysis from different disciplinary backgrounds. However, comparing the results from these and providing cohesive and integrated recommendations for stakeholders to take up is challenging. Using the framing of results through the levels of knowledge generation may offer a way forward for the nexus community in general and the wastewater community, in particular.

Based on the findings of this research, moving forward in sustainable wastewater treatments systems it is recommended to:

(1) use types of analysis beyond technical assessments and from various disciplinary backgrounds to determine the state of affairs;
(2) design the activities used in the types of analysis in a manner that allows for knowledge generation and its extraction/representation;
(3) work in a participatory way to co-create knowledge across all stakeholders including the project team.

While this may be time-consuming, it may ultimately be a useful investment and provide more sustainable infrastructure which, in turn, may lead to more sustainable systems. This may require a new set of engineers that expand their technical skills with social assets; a task that may also need to be taken up in higher education.

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