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Adapting Santiago Method to Determine Appropriate and Resource Efficient Sanitation Systems for an Urban Settlement in Lima Peru

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Abstract: The pre-selection of locally appropriate sanitation technologies and systems is crucial for strategic sanitation planning as any decision is only as good as the options presented. One approach that allows us to systematically consider the local conditions and a diverse range of conventional and novel technologies and systems is the *Santiago* method. In this paper, we discuss whether the Santiago method can be applied to the case of Latin America and what we would gain from this application. We do so by expanding the *Santiago* technology library with technologies that have been shown to be promising in metropolitan areas of Latin America, such as *condominial* sewer, container-based sanitation, and activated sludge. We then apply *Santiago* to the semi-informal settlement Quebrada Verde (QV) in Lima, Peru. Using Santiago, we were able to generate 265,185 sanitation system options from 42 technologies and 18 appropriateness criteria. A set of 17 appropriate and divers are then selected. The diversity is defined by 17 system templates. To further evaluate these 17 systems, resource recovery and loss potentials are quantified. Higher nutrients (nitrogen and phosphorus) and total solids recovery are observed for systems that combine urine diversion and biofuel production. The case of QV shows that the *Santiago* method is applicable in the Latin American context.

Keywords: informal settlement; Lima; sanitation; Santiago; urban water management

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1. Introduction

The World Health Organization (WHO) describes a safe sanitation system as a system that separates excreta from human contact at all levels of the sanitation chain. Entire sanitation systems include technologies for every step of the chain, including the user interface, collection and storage, transport, treatment, as well as end-use and/or disposal. A safely managed service is defined as the use of unshared improved facilities and where the excreta are disposed of safely on-site or transported and treated off-site [1]. While sanitation is understood as access to and use of facilities and services [2], sustainable sanitation is described as an approach to allow a broad range of criteria to be included in design considerations to achieve long-term universal and equitable services [3]. The significant criteria to define sustainable sanitation are health and hygiene, technical appropriateness, social and institutional acceptance, financial viability, and protection of the environment and natural resources [4]. Provision of sustainable sanitation in rapidly growing urban areas in Asia, Africa, and Latin America can be very challenging for several reasons, including the difficulty of finding appropriate technologies for different types of settlement (e.g., planned and unplanned settlements) [5]. The fact that conventional sewer systems are not the one-for-all solution in urban settings makes on-site systems a viable option to accommodate the need for urban sanitation provision in a special context, such as densely populated settlements [6]. This condition has also led to the development of novel options that are not only potentially more appropriate (independent from water, energy, and sewers) but also less capital intensive and more sustainable in terms of resource protection through the possibility of recovering nutrients, energy, and water. Examples of such more innovations are *condominial* sewers [7] or container-based sanitation systems [8].

As more technology options and decision criteria find their way into practice, it becomes increasingly difficult to select the locally most appropriate and potentially most sustainable system options. There exist several Structured Decision-Making (SDM) [9] approaches such as CLUES [10] or Sanitation21 [11] that can help in such a situation by combining engineering with decision analysis. Such approaches cover six generic decision steps including: (1) understanding the decision process; (2) defining decision options; (3) identifying decision options; (4) evaluating decision options regarding main objectives; (5) selecting the preferred options; and (6) implementation and monitoring. In steps (4) and (5) different multi-criteria decision analysis (MCDA) methods can be used to identify and negotiate trade-offs and to balance opposing interests. Examples of evaluation methods include the CLUES Tool D17.1 [12] or SSI [13] or WASSI [14]. However, any decision is only as good as the options presented. So far, the identification of sanitation system planning options (step 3) was left to experts who lack the knowledge and data to systematically consider the diverse and wide range of currently available and novel technologies and system configurations, the multiple criteria, and the local conditions. This leads to several shortcomings, including a lack of transparency and knowledge as well as preference bias.

The consideration of specific local preconditions as a basis for identifying appropriate technologies has long been introduced to lead to more effective project implementation [15]. The identification of locally appropriate technologies and systems requires the consideration of various boundary conditions (e.g., socio-economic conditions, geographical or climatic conditions) and practical requirements (e.g., operation and maintenance requirements) [16]. The situation is particularly challenging in rapidly expanding urban areas of developing countries where most of the current population growth is taking place. These areas are characterized by high density, a lack of basic services, such as drinking water and sanitation services, and a lack of human and financial resources for planning, leading to a high degree of informality. Slums, informal or unplanned settlements, are one of the most long-lasting urbanization challenges of this century [17]. The peri-urban area of Lima, the capital of Peru, includes many examples of such informal settlements [18]. In particular, the informal settlements in the lower part of the Lurin River Basin have led to environmental problems, mainly due to irresponsible human activities (e.g., lack of sanitation, pollution of surface and groundwater) [19].

One of these settlements is Quebrada Verde (QV) in Lima, located in the lower part of the Lurin River Basin in the Pachacámac District. QV is a semi-informal settlement with 800 inhabitants, borders on the north and the west with highlands, and on the east and the south with the agricultural area and Lurin River. Lurin is one of the three main rivers in Lima. The settlement is equipped with a mix of urban, rural, and peri-urban infrastructures. The characteristics of soil in QV varied between the hillside for grazing and the lowland for agriculture. Agriculture is still the primary source of income for many settlers in the peri-urban areas of Lima [20] and represents a significant percentage of economic activities [19]. The community of QV is part of the district Pachacámac. It receives inadequate drinking water and lacks a public sewer system. This leads to health risks. Parasites and diarrheal diseases are reported [21].

An effort to provide safe sanitation service to such settlement through a container-based sanitation system has been shown by a social venture in Lima, x-runner. This system relies on a urine-diverting dry toilet (UDDT) with centralized emptying and treatment. However, these innovations are restricted by the absence of suitable regulations for their services that require different organization than centralized sewer systems [22]. The provision of safe sanitation services for Lima's informal settlements is a dilemma for both communities and regulators. Both parties are seeking a long-term solution, yet the implementation might not come soon. Alternative services, e.g., container-based sanitation or the *condominial* sewer, can be something to look forward to [23]. The *condominial* system offers lower capital and operating costs by reducing the size of those technical aspects [24]. *Condominial* sewer could cut half of the cost of the conventional sewerage per person. It is the best option to apply in a high-density area where septic tanks are not present [25]. Another study mentioned that one could save up to 65% more pipe installation costs than with the conventional system [26]. Another technology that has long been used for treating wastewater is an activated sludge process. Activated sludge systems, such as conventional activated sludge and anaerobic-aerobic systems in sequencing batch reactors (SBR), have been implemented in Lima. The conventional activated sludge system is particularly applied at the wastewater treatment plant (PTAR) at PTAR Cieneguilla in the district of Cieneguilla in the Lurin Valley [27].

There exist several sanitation technologies and systems that have the potential to be more appropriate and more sustainable than conventional systems, such as sewer systems (too expensive) or pit latrines (polluting groundwater). However, as mentioned above, experts often lack the knowledge or data to consider those technologies and systems during the planning process. Moreover, there exists a lack of understanding on which criteria can be used for evaluating the different options. There are simply too many possible system configurations and criteria to manually consider when developing options as an input into strategic planning.

One approach that allows to systematically consider a broad range of conventional and novel technology options and local conditions for the pre-selection processes is the *Santiago* method [28]. The *Santiago* method consists of software (SANitation sysTem Alternative GeneratOr), a technology library, and a methodology to integrate these tools into a strategic planning process [29]. It is designed to support step 3 of SDM (see above) by allowing us to systematically and transparently pre-select system planning options and provides resource recovery potentials as one indicator for the detailed evaluation (step 6 of SDM). The software first allows us to evaluate the appropriateness of potential technologies based on some technical and non-technical screening criteria, to build all valid system configurations from the appropriate technologies (typically more than 100,000 from a set of 40 technologies), to pre-select a set of systems that is of manageable size, locally appropriate and diverse, to reveal trade-offs. Additionally, the nutrient, water, and total solid flows, recovery, and loss potentials can be quantified as one sustainability indicator [29–31]. The main advantage of using the software is the possibility to deal with a diverse and very large set of technologies and corresponding system configurations. Moreover, the software and its library provide international literature data and expert knowledge on technology appropriateness and substance flows and match to the local context for more empirical decision making. The library can easily be expanded to include future technology innovations and additional sanitation products. Using a software approach also allows us to systematically consider uncertainties related to the technologies or the local context, making it applicable at an early planning phase.

Santiago was developed iteratively in collaboration with case studies in Nepal (2016/2017), Ethiopia (2016 and 2019), Peru (2019), and South Africa (2020) [29,30]. The case studies allowed us to provide immediate feedback to future users and to evaluate the methods. The case studies also showed that *Santiago* could provide several benefits. For instance, inappropriate options are eliminated at the beginning, streamlining the process. Moreover, the options space is expanded with systems that experts would not have thought of or did not even know about. The diversity of the set of options is guaranteed to help to reveal and discuss trade-offs during further evaluation (e.g., resource recovery versus hygiene).

This research aims to answer two research questions:

(1) Can *Santiago* be applied adapt to the case of rapidly growing semi-informal metropolitan settlements of Latin America illustrated by the case of the semi-informal settlement Quebrada Verde (QV) in Lima, Peru?

(2) What do we learn from this application for the case of QV and what are the expected gains (advantages) for other cases in Latin America?

To answer these questions, we expand the *Santiago* library with technologies that have shown to be promising in metropolitan areas of Latin America (e.g., *condominial* sewer and activated sludge [32–35] and apply the *Santiago* methodology to QV. We then analyze the appropriateness of different technologies for QV, select a diverse and appropriate set of 17 sanitation systems built from the technologies, and evaluate their resource recovery for four substances (nitrogen, phosphorus, total solids, and water). We then reflect on the plausibility of the results and conclude with the potential gains that the application of *Santiago* can bring to the case of QV and other cases in Latin America.

2. Materials and Methods

2.1. Santiago Method

The *Santiago* method used in this research consists of software, a technology library, and a methodology for data collection to integrate the software and the library in a structured decision-making process (SDM) [9], such as CLUES [10] or Sanitation 21 [11]. The software includes four modules: (1) the technology appropriateness assessment (TechApp); (2) the system builders (SanSysBuilder); (3) the option selector (OptionSelector); and (4) the mass flows quantification (SanSysMassFlows). These modules are documented in [30,31]. The models are executed in the R and Julia and can be accessed freely from https://github.com/Eawag-SWW/TechAppA (accessed on 1 March 2021) and http://github.com/Eawag-SWW/SanitationSystemMassFlow.jl (accessed on 1 March 2021). The technology library is available at ERIC: https://doi.org/10.25678/0000SS (accessed on 1 March 2021) [36]. The integration with the planning process is documented in [29]. The output of this procedure will only tell us whether the technologies are appropriate to be implemented in a given case and are not intended to replace experts' knowledge for the detailed design and implementation of the technologies. The steps used in this paper are summarized in Figure 1. The overall goal is to get a set of appropriate sanitation system options that are diverse in terms of different technological approaches and information regarding resource recovery and loss potentials for these systems. These can be used as an input into a more detailed sustainability analysis using, for instance, multi-criteria decision analysis [37]. In the following, we are briefly summarizing the software based on the supplementary material of [29].

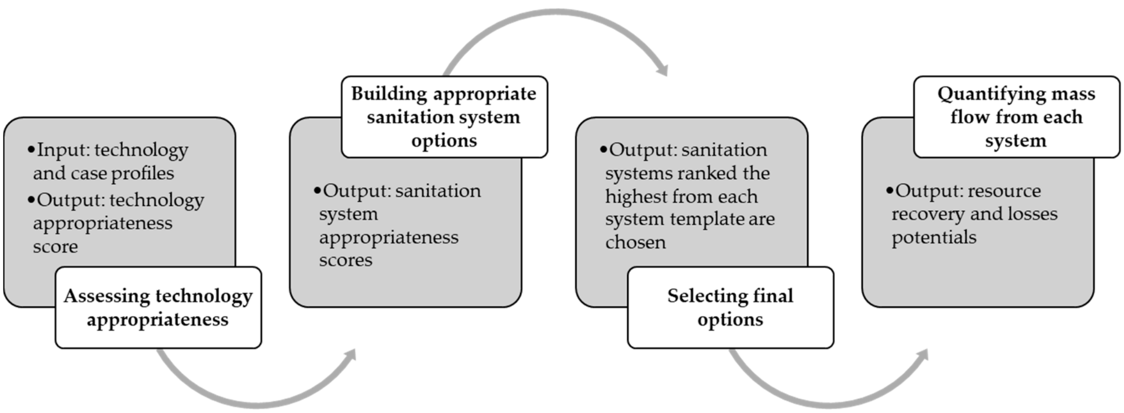

Figure 1. The *Santiago* procedure according to [29,30].

***Santiago* technology library:** A sanitation technology is defined as any process, infrastructure, method, or service that is designed to contain, transform, or transport sanitation products. It is characterized by its name, the input and output products (e.g., blackwater or greywater -> septic tank -> sludge and effluent), as well as the screening criteria attributes describing its technology appropriateness profile (e.g., water and energy requirements, frequency of operation and maintenance, etc.). In the technology library, there exist the appropriateness profiles of 41 technologies and 27 screening criteria covering, e.g., technical, physical, demographic, socio-cultural, financial, capacity, and managerial aspects [36]. There also exist the transfer coefficients for phosphorus, nitrogen, total solids (as an indicator for organics and energy), and water for each technology. The transfer coefficients and the appropriateness profiles are generic and can be reused for any other application. Also, the library can easily be extended to capture future technology innovations.

Technology appropriateness assessment (TechApp): The appropriateness of technology for a given application case is defined by matching the technology profile to the application profile. The profiles are defined by the screening criteria. For each screening criterion, a pair of appropriateness attributes are required: a "technology attribute" and a "case attribute" (e.g., the performance of a technology needing a particular energy supply and energy availability in the given application case). The attributes cannot be described by a single value because temporal and regional variabilities exist and because of other uncertainties (e.g., data availability, future evolution). To account for these uncertainties, probability functions are used to parameterize the attributes. Each pair of technology and case attributes consist of one probability density function (e.g., the water availability for a given case) and one conditional probability function (e.g., the performance of technology, given particular water availability). One attribute function describes the requirements and the other conditions that have to be matched. The type of possible probability functions (e.g., range and category functions) that can be used as attributes are explained in the technology library [32]. The overlap of the attribute functions defines the screening criteria appropriateness score between 0 and 1. By aggregating all criteria scores for a given technology and application case, the technology appropriateness score (TAS) is obtained. Again, it is a number between 0 and 1, that expresses the confidence in the appropriateness of the technologies and sanitation systems for a given application case.

System builders (SanSysBuilder): A sanitation system is defined as a set of compatible technologies that, in combination, manage sanitation products from the point of generation to a final point of reuse or disposal. The technologies contained in a system are organized into functional groups: the toilet user interface (U), on-site storage (S), conveyance (C), treatment (T), and reuse or disposal (D). A technology belonging to U is always a source, while a technology belonging to D is always a sink. In this paper, we focus on toilet sources only. However, additional sources, such as taps, drainage, or organic solid waste, can also be included. A sanitation system is valid if it contains only compatible technologies and every sanitation product either finds its way into a subsequent-technology or a sink [30]. Two sanitation technologies are compatible if the output product of one can be the input product of the other [38]. The SystemBuilder is an algorithm that allows automatic generation of all valid sanitation system configurations from a set of potential technologies. The sanitation system appropriateness score (SAS) is calculated by aggregating the TAS of every technology of the system using a weighted geometric mean [30].

Option selector (OptionSelector): The automated generation of sanitation system options typically leads to more than 100,000 options for a set of 40 technologies. The aim is to identify a set of sanitation system options which is of manageable size and is also appropriate and diverse. The SDM process and the model complexity of methods used in steps 4 and 5 define the manageable size, which is typically between 3 and 50. The appropriateness is defined by the SAS. To characterize the diversity, we use system templates. A system template defines a class of sanitation systems with similar conceptual characteristics. The OptionSelector uses nine binary conditions (e.g., "produces biofuel" and "includes transport") to define 19 system templates [31], including simple onsite, urine diversion, biofuel production, and blackwater systems of different degrees of centralization (see Table 1 for an overview). Each system can be assigned to one unique template. It then selects the system with the highest SAS from each template. Only 17 systems are applicable in this study. System templates 7 and 8 were omitted as there were no systems matched in these groups.

Table 1. System template based on [31].

Group	Name	System Template Profiles	
Onsite simple	ST1	Dry onsite storage with sludge production without effluent transport	Onsite single pits with sludge production and treatment.
	ST2	Dry onsite storage with sludge production with effluent transport	Onsite single pits with sludge production and with effluent transport.
	ST3	Dry onsite storage and treatment without sludge production	Onsite storage of excreta and transformation to either pit humus or compost.
Urine	ST4	Dry onsite storage without treatment with urine diversion without effluent transport	Simple onsite storage of dry or wet toilet products with sludge production (e.g., single pits, double pits, twin pits) with onsite effluent management (e.g., soak pits).
	ST5	Dry onsite storage without treatment with urine diversion with effluent transport	Simple onsite storage of dry or wet toilet products with sludge production (e.g., single pits, double pits, twin pits) with effluent transport to offsite management.
	ST6	Dry onsite storage and treatment with urine diversion	Urine diversion dry toilets (UDDTs) or dry composting systems with urine diversion.
	ST7	Onsite blackwater without sludge and with urine diversion	Onsite composting systems with urine diversion.
	ST8	Offsite blackwater treatment with urine diversion	Sewer systems with urine diversion.
Biofuel	ST9	Onsite biogas, biochar, or briquettes without effluent transport	Biogas reactors or other fuel producing technologies (e.g., LaDePa) with onsite effluent management (e.g., soak pit).
	ST10	Onsite biogas, biochar, or briquettes with effluent transport	Biogas reactors or other fuel producing technologies (e.g., LaDePa) where effluent goes to simplified sewer.
	ST11	Offsite biogas, biochar, or briquettes without blackwater transport	Offsite production of biofuel from pit humus or sludge (e.g., from septic tanks).
	ST12	Offsite biogas, biochar, or briquettes with blackwater transport	Offsite co-digestion of blackwater collected through sewer lines.
Blackwater	ST13	Onsite blackwater without sludge and without effluent transport	Blackwater stored, dewatered, and transformed to compost or pit humus (e.g., twin-pits), onsite effluent management (e.g., soak pit).
	ST14	Onsite blackwater without sludge and with effluent transport	Blackwater stored, dewatered, and transformed to compost or pit humus (e.g., twin-pits), effluent goes to simplified sewer or similar.
	ST15	Onsite blackwater with sludge without effluent transport	Storage technologies including some basic treatment (e.g., septic tank) with onsite effluent management (e.g., soak pit).
	ST16	Onsite blackwater with sludge and effluent transport	Storage technologies including some basic treatment (e.g., septic tank) with effluent going to simplified sewer or similar.
	ST17	Onsite blackwater treatment without effluent transport	Compact onsite wastewater treatment units (e.g., SBR) with onsite effluent management.
	ST18	Onsite blackwater treatment with effluent transport	Compact onsite wastewater treatment units (e.g., SBR) with effluent going to simplified sewer or similar.
	ST19	Offsite blackwater treatment	(Semi-)centralized sewer system

ST = system template.

Quantification of mass flows (SanSysMassFlows): Resource recovery potentials and resource emissions are important indicators for detailed evaluation and options. The SanSysMassFlows module is based on a simplified substance flow modelling algorithm for the ex-ante quantification of total phosphorus, total nitrogen, total solids (indicators for organics and energy), and water balances [31]. We are aware that these are not the only performance indicators required for evaluating the primary decision criteria. The algorithm uses transfer coefficients for each technology and substance defined in the technology library [36] and then propagates the inflows through the entire system. This allows for calculating how much of the entering substance is lost to the soil, air, or water, and how much can potentially be recovered.

Integration with planning: The required inputs to run the algorithm above are a locally adapted technology library and the application case profile. The adapted technology library contains potential technologies, their appropriateness profiles, and their transfer coefficients. The appropriateness profiles are defined by the parameterized appropriateness attributes. For this, one has to select the screening criteria that are relevant for the particular case (e.g., 10 to 20 criteria). The application case profile consists of the parameterized attribute functions for each screening criteria for the case. For instance, to evaluate the screening criteria "energy", each technology has a function defining its performance given particular energy availability and the case profile contains an attribute defining the local energy availability. For example, the *condominial* sewers are energy independent, and their attribute function is a continuous function of 100% (1) performance from zero to 24 h of energy per day. The energy availability in QV varies from zero to 24 h (intermittent), with the most common supply ranges between 22–24 h.

2.2. Application Case: QV

The chosen project location was part of the sustainable, fair, and environmentally sound drinking water supply for prosperous regions with water shortage (TRUST) project located in Lima, Peru. The TRUST project is funded by the German Federal Ministry of Education and Research (BMBF) as part of the Global Resource Water (GRoW) program. The project involved various research organizations, companies, administrations, and NGOs in Germany and Peru. You can find further information on the project and its partners at http://trust-grow.net (accessed on 1 March 2021). The project itself focused on the Lurin river catchment in the water-shortage region of Lima, Peru [39]. There is a total of 86,974 households within the area of Lurin Valley, with 53% of the households are connected to the public water supply network, 32% are supplied by water tankers, 9% are supplied by groundwater, and the rest is supplied from the nearest rivers and other sources. Of the households in Lurín valley, 51% are connected to a public sewer system and 45% have decentralized systems like septic tanks, latrines, and cesspools (4%, other) [40].

2.3. Data Collection

The main inputs are: (1) the set of potential technologies; (2) the screening criteria that can be used to evaluate the appropriateness of a given technology; (3) the data describing the local conditions; and (4) the inflow for the substances required to quantify mass flows; and (5) the number of options that should be pre-selected.

2.3.1. Potential Technologies

A total of 42 technologies were evaluated regarding their appropriateness (see Table 2). These technologies were taken from the technology library [36], except for the five technologies fossa *alterna*, *condominial* sewer, anaerobic filter, trickling filter, and activated sludge, which were independently developed for this research. *Condominial* sewer and activated sludge are particularly highlighted in this study as both technologies are common in Latin America. Model inputs used in this research are provided in Supplementary Materials.

Table 2. List of potential technologies grouped by its functional groups [1].

Groups	Technologies
U	Urine-diverting dry toilet; dry toilet; pour-flush toilet; cistern-flush toilet
S	Urine storage tank; dehydration vault; faeces storage chamber; single pit; twin pits; composting chamber; vermicomposting; septic tank; fossa *alterna*
C	Motorized transport of urine; human-powered transport of urine; motorized transport of dry material; human-powered transport of dry material; conventional sewer; solids-free sewer; *condominial* sewer
T	Urine bank; sludge drying bed; faeces drying bed; anaerobic baffled reactor; anaerobic filter; sequencing batch reactor; trickling filter; activated sludge; co-composting; biogas reactor; waste stabilization pond, constructed wetland
D	Application of urine; application of faeces; application of compost; application of processed sludge; biogas combustion; leach field; soak pit; irrigation; surface solid disposal; surface water disposal

[1] User interface (U), collection and storage (S), conveyance (C), treatment (T), and use and/or disposal (D).

2.3.2. Appropriateness Criteria

A total of 18 screening criteria were independently formulated and we consulted with experts instead of defining it through a workshop with local stakeholders. The reason is that the experts acquired sufficient information required for this research through the TRUST project substituting the stakeholders' opinions. These are water supply, energy supply, water supply disruption, energy supply disruption, frequency of operation and maintenance (O&M), spare parts supply, temperature, flooding, vehicular access, slope, soil type, groundwater depth, surface area on-site (for decentralized technologies), surface area off-site (for centralized technologies), construction skills, design skills, O&M skills, and management. The case and technology profiles used in this study are documented in the supplementary material.

Quantification of technology attributes: To quantify the technology attributes, mostly data from the technology library was used [36]. For the five newly added technologies, literature research and our own judgment were used to define the attribute functions.

Characterizing the application case profile: The attribute functions for the case profile were defined based on data collected from the literature review and experts. The literature data was provided by the baseline study of the GRoW's TRUST project and acquired from the BMBF.

2.3.3. Substances, Inflows, and Transfer Coefficients

For the mass flows quantification, mass inflows for each type of toilet source (U) and transfer coefficients for each observed substance of each technology should be defined in the beginning. These substances are total phosphorus (P), total nitrogen (N), total solids (S), and water (W). Inflows were taken from the technology library, which provides an internationally valid average. For substances P, N, and S, the inflows are the same for all sources (FG-U), namely, 0.5 tons year^{-1}, 3.2 tons year^{-1}, and 20.4 tons year^{-1}, respectively. Water inflows for wet sources (pour- and cistern-flush toilets) are 3928.6 and 17,944.6 tons year^{-1}. Water inflows for dry sources (dry toilet and UDDT) are the same, 424.6 tons year^{-1}. The mass inflows were calculated for 800 inhabitants of QV, using references for loads per inhabitants from the ATV A131 guideline [41]. References for transfer coefficients used in this study were primarily taken from the technology library, except for fossa *alterna*, *condominial* sewer, anaerobic filter, trickling filter, and activated sludge, and are summarized in Supplementary Materials. The mass flows calculation was done for all valid sanitation systems using 150 Monte Carlo (MC) runs. Standard deviations were used to measure uncertainties in the result of mass flow quantifications and compared with the result from other studies.

2.3.4. Number of Options

The manageable number of pre-selected systems was set to 17, which corresponds to one from each system template.

2.4. Data Analysis

Data analysis was carried out in the R and Julia environment [42,43]. The output of the *Santiago* method was generated from the Julia environment and then later analyzed using the statistical software program, R.

3. Results and Discussion

The main results include the technology appropriateness scores (TAS), all valid system configurations and the system appropriateness scores (SAS), the set of selected systems, and the resource recovery and loss potentials of all systems. In the following, we briefly present and discuss these results and discuss two technologies that were added to the *Santiago* library particularly for this case: the *condominial* sewer and the activated sludge technology.

3.1. Generating Appropriate Sanitation System Options

The technology appropriateness scores for the 42 technologies varied between 0.669 (motorized transport urine and wet) and 0.981 (biogas combustion). None of the technologies was fully inappropriate. Lower appropriateness scores were mainly obtained for the criterion water requirements, disruption of water supply, energy requirements, the disruption of energy supply, vehicular access, and management. To a lower extent, slope, soil type, design skills, and frequency of operation and maintenance had a sensitive impact on the scores. Using the 42 technologies, 265,185 valid sanitation system configurations were generated. For the two wet sources, pour-flush and cistern-flush toilets, 100,443 systems were generated which are identical because both sources have the same output product (blackwater). For the UDDT source, 57,188 systems were generated, and for the dry toilet 7111 systems. The number for pour flush toilet is smaller because there exists less possible combinations within the potential techs that allow covering the rest of the treatment chain (functional groups S, C, T, D). The number of generated systems is similar to two previous *Santiago* case studies (e.g., [29,44]). The 265,185 were then assigned to the 19 templates from [44]. No system for ST-7 and ST-8 was generated because these templates would require a urine diversion flush toilet that was not considered in this case. To pre-select a set of sanitation system options, the system with the highest SAS was selected from each of the remaining 17 templates. Using the templates, it was ensured that the set of selected systems is diverse in terms of the type of system and degree of centralization. The diversity is a precondition allowing to highlight trade-offs regarding different decision objectives in a detailed evaluation later in the planning process (see Figure 2 for insights).

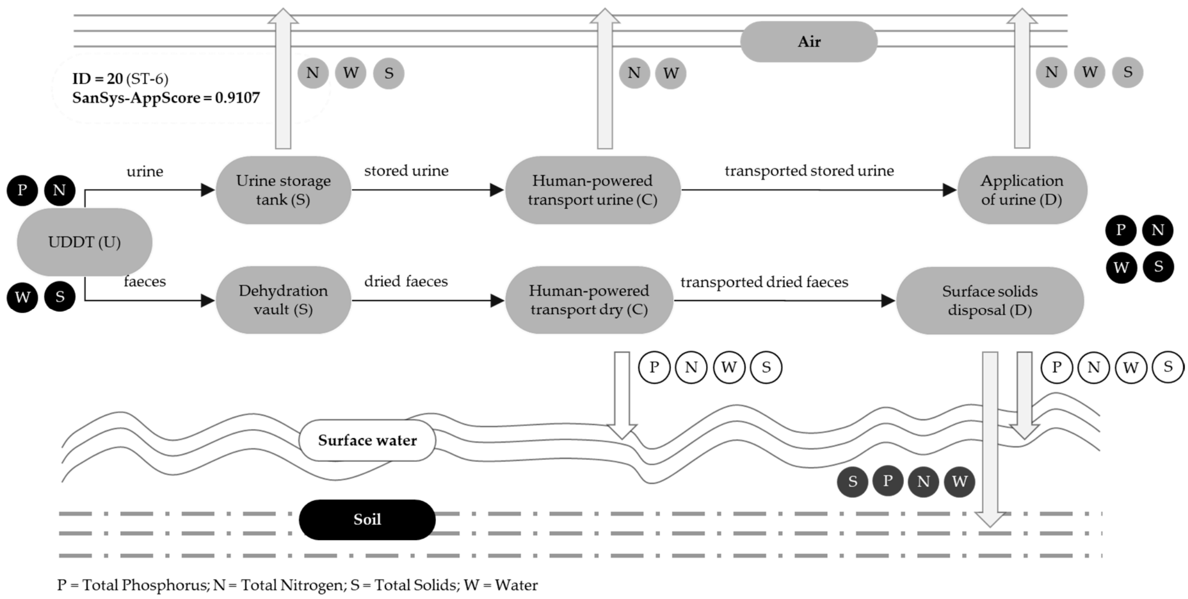

Figure 2. Illustration of one of the selected system options and the possible direction of substances recovery and losses along the sanitation system chain.

The set of selected systems is listed in Table 3. All selected systems have a high appropriateness, although the systems from ST-9 and ST-11 are the only systems that show an SAS of 0.9. None of the selected systems includes the cistern-flush toilet, even though the cistern-flush toilet itself does not have a particularly low SAS. Thus, probably the technologies required to build entire systems from the cistern-flush are less appropriate. It shows that appropriateness should not be looked at a single technology level, but has to be compared looking at each entire system as already shown in [44]. Nevertheless, the cistern-flush toilet has a lower TAS than the other sources mainly because of its higher water requirement. QV is a water-scare area, and more than half of the population relies on water supplied from water trucks or pylon.

Table 3. List of technologies of the selected sanitation systems grouped by its functional groups.

ID	Score	User Interface	Collection and Storage	Conveyance	Treatment	Use and/or Disposal
20 (ST-6)	0.91	UDDT	urine storage tank; dehydration vault	human-powered transport urine; human-powered transport dry	-	application of urine; surface solids disposal
120 (ST-11)	0.90	UDDT	urine storage tank; faeces storage chamber	human-powered transport urine; human-powered transport dry	biogas reactor	application of urine; surface solids disposal; biogas combustion
152 (ST-9)	0.90	UDDT	urine storage tank; faeces storage chamber	human-powered transport urine; human-powered transport dry	biogas reactor	application of urine; surface solids disposal; biogas combustion
8430 (ST-4)	0.87	UDDT	single pit; urine storage tank	human-powered transport urine; human-powered transport dry	co-composting	application of urine; surface solids disposal
9368 (ST-5)	0.86	UDDT	single pit; urine storage tank	human-powered transport urine; human-powered transport dry; solids-free sewer	sludge drying bed	application of urine; surface solids disposal; irrigation
57614 (ST-1)	0.84	dry toilet	single pit	human-powered transport dry	co-composting	surface solids disposal
58090 (ST-2)	0.84	dry toilet	single pit	human-powered transport dry; solids-free sewer	sludge drying bed	surface solids disposal; irrigation
63628 (ST-3)	0.89	dry toilet	vermicomposting	human-powered transport dry; solids-free sewer	-	surface solids disposal; irrigation
67975 (ST-13)	0.88	pour-flush	twin pits	human-powered transport dry	-	surface solids disposal
69058 (ST-14)	0.87	pour-flush	vermicomposting	human-powered transport dry; solids-free sewer	-	surface solids disposal; irrigation
101590 (ST-19)	0.85	pour-flush	-	*condominial* sewer	constructed wetland; co-composting	surface solids disposal; irrigation
101596 (ST-12)	0.85	pour-flush	-	*condominial* sewer	constructed wetland; biogas reactor	surface solids disposal; irrigation; biogas combustion

Table 3. *Cont.*

ID	Score	User Interface	Collection and Storage	Conveyance	Treatment	Use and/or Disposal
132296 (ST-16)	0.87	pour-flush	-	human-powered transport dry; solids-free sewer	anaerobic filter; co-composting	surface solids disposal; irrigation
134278 (ST-15)	0.86	pour-flush	-	human-powered transport dry;	anaerobic filter; co-composting	surface solids disposal; irrigation
142274 (ST-10)	0.87	pour-flush	-	human-powered transport dry; solids-free sewer	anaerobic filter; biogas reactor	surface solids disposal; irrigation; biogas combustion
143088 (ST-18)	0.85	pour-flush	-	human-powered transport dry; solids-free sewer	sequencing batch reactor	surface solids disposal; irrigation
143118 (ST-17)	0.84	pour-flush	-	human-powered transport dry;	sequencing batch reactor	surface solids disposal; irrigation

The system integrating the UDDT as a source showed the highest appropriateness score. This is not only due to the high score of the UDDT (highest within FG-U) but also because of the comparatively higher TAS of the technology combinations that allow building valid system configurations from this source.

3.2. Quantifying Substance Recovery and Losses Potential

The substance flow module from *Santiago* was then applied to all valid systems and to quantify recovery and loss potentials for all the four substances P, N, S, and W, as described in [31]. Here we analyze only the results for the 17 selected systems. Figure 2 illustrates an example of the results: for each substance and technology, it is quantified to know how much is either transferred or lost to the soil, water, or the air. In the sink (FG-D), the substance is then either lost to one of these three compartments or recovered. By summing up all losses and recoveries over a system, the total recovery and loss ratio per system are obtained. Each ratio also comes with a standard deviation which results from the modelling of the variability of the transfer coefficients of the technologies which represent the variability of underlying literature data.

Figure 3 shows the recovery potentials and losses from all 17 selected systems. For P, N, and S, we present the ratio [%]. For water, we provide the absolute volume [$m^3 year^{-1}$], as the relative recovery does not provide any useful information (e.g., comparing dry toilets with pour-flush). Again, the systems with the source UDDT perform the best (ST-4 to ST-9; ST-11). For example, the system ID-20 (ST-6) is expected to recover 58% of P (0.3 tons year^{-1}), 72% of N (2.3 tons year^{-1}), 62% of S (12.7 tons year^{-1}), and 84% of water (355.3 tons year^{-1}) from the system. The systems ID-120 (ST-11) and ID-152 (ST-9) are also integrating the UDDT but further combine this with biofuel production. These systems show a particularly high recovery potential, confirming the results from [44]. In practice, such systems are often called the container-based systems and have most recently been shown to be a promising alternative to conventional solutions in informal settlements in Kenya and Peru [22]. The system appropriateness, together with resource recovery, allows us to further narrow down the set of selected systems.

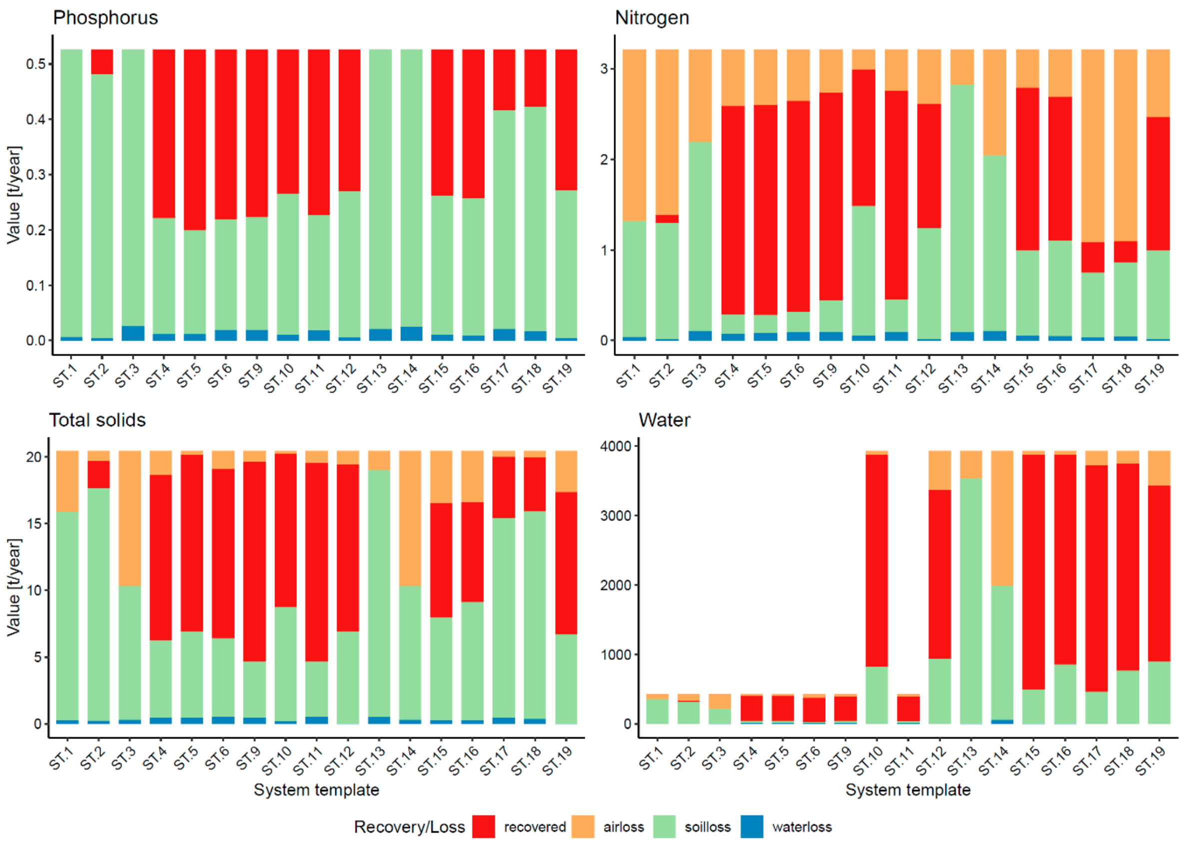

Figure 3. Stacked-bar graph of mass recovery and losses potentials for the selected systems per year.

The system with dry toilets, such as the system ID-57614 (ST-1), has a significant amount of leakage or evaporation in the technologies of FG-S (mainly single pits and vermicomposting). Also, some systems include only sinks that do not allow for recovery, resulting in zero recovery potential (e.g., ID-57614 from ST-1 and ID-63628 from ST-3). Nevertheless, if vermicomposting is combined with reuse of the final compost and reuse of the effluent for irrigation (e.g., ID-63628) then this system would allow recovering nutrients and organics safely, as total coliforms are said to be eliminated [45].

For the systems with the cistern-flush toilet, the amount of water that can be recovered is much higher. However, these systems also require much more water as an initial input. For instance, system ID-134278 (ST-15) not only is estimated to recover 86% of N but also the highest amount of water among all systems (3.4 million $m^3 year^{-1}$). The system applies an anaerobic filter for treating wastewater, followed by co-composting for treating the sludge produced by the anaerobic filter. Compost is reused in agriculture, and the treated effluent is used for irrigation. However, this system is relatively short, meaning it involves few treatment steps only and precaution should be taken as the effluent of an anaerobic filter does not meet the WHO standard for irrigation [46].

Based on the above-described results, we could further narrow down the pre-selection of the technologies. In case of resource recovery, in general, is intended to be optimized, then the UDDT systems ID-20 (ST-6) and ID-152 (ST-9) would be preferred, as indicated in Table 3. However, in case there is a particular preference for the recovery of a certain substance, such as water, then probably system ID-134278 (ST-15) would be given preference. However, it is significant to note that appropriateness and resource recovery are often not the only decision criteria, but other aspects such as costs or quality/marketability of the end-product also play an important role and could be used for the final selection of the preferred option.

3.3. Additional Technologies

Condominial sewer also appears in the list of the 17 selected systems in the wet system ID-101590 (ST-19) and ID-101596 (ST-12). This type of sewer also has been widely implemented in Latin American countries, such as Brazil [34,47], Honduras [48], Bolivia [35], and Peru [49]. The TAS of the *condominial* sewer was comparatively high (0.91) and was only highly influenced by two attributes, frequency of O&M and management. *Condominial* sewer requires a lower water requirement and engineering cost compared to the conventional sewer. However, the lowest engineering costs tend to come with a higher cost of social intermediation, and hence, create a trade-off [35]. In the case study of QV, household management is more preferred compared to community participation. If systems with *condominial* sewers are selected, the higher community participation could be justified by the reduction of the O&M. Both selected systems system ID-101590 (ST-19) and ID-101596 (ST-12) use a constructed wetland to treat the wastewater. The first system uses co-composting for the sludge the other uses a biogas reactor. The end-products, which are stabilized effluent and stabilized sludge, can be reused for irrigation and fertilization for resource recovery. In the PROSANEAR project implemented in multiple cities in Brazil, the *condominial* systems were coupled by stabilization ponds, up-flow anaerobic sludge blanket (UASB), or communal septic tanks [50]. *Condominial* sewers combined with decentralized horizontal subsurface flow constructed wetlands have been implemented by the Peruvian state-owned water utility, SEDAPAL, in some peri-urban areas in Lima [51]. If horizontal subsurface flow constructed wetlands are intended to be used as a primary treatment, the effluent shall be frequently monitored whether it meets the standard of wastewater reuse for irrigation. On the other hand, the French system (vertical flow constructed wetland) is proven to treat raw sewage for decades, as reported by [52]. According to [21], there is already a small-scale horizontal subsurface constructed wetland around QV used for treating wastewater from tourist attractions.

The activated sludge process proposed in this research scored only 0.71 and was included below the 25th percentile of technologies in the FG-T. Major attributes influencing the score were energy supply required, energy supply disruption, and space requirements. Not only water supply, the electricity for water provision and hygienic service also faced intermittent supply in Pachacámac [40]. QV lies at an altitude of 200 m above sea level. The settlement is located on the highland with a slope range between 0 to 40% and an average of 18%. The availability of the surface area between houses and projected facility sites for the centralized system (e.g., using activated sludge) is also moderate. If in the future the responsible stakeholders could free some lands for the wastewater treatment plant and water as well as electricity provision are sustained, this technology can be considered.

4. Conclusions

The *Santiago* method was successfully applied to the case of the semi-informal settlement QV in the metropolitan area of Lima, Peru. To do so, five technologies were added to the *Santiago* library [36] and in total 42 conventional and new technologies were considered. A total of 18 appropriateness criteria were quantified for QV and systematically compared to the 42 technologies. No technology was fully inappropriate, but biogas combustion showed the highest TAS (0.981) and motorized transport showed the lowest TAS (0.669). The criterion water requirements, disruption of water supply, energy requirements, the disruption of energy supply, vehicular access, and management, turned out to have the most sensitive effect on the TAS. Out of 42 technologies, the method could generate 265,185 appropriate sanitation system options. From these systems, 17 systems were selected as an input into the sanitation planning process. The selected systems are locally appropriate, diverse, and limited in number. The appropriateness is defined by comparing the technology appropriateness profile from the *Santiago* technology library with the appropriateness profile of QV. The diversity is defined by 19 system templates, including simple onsite, urine diversion, biofuel production, and blackwater systems of different degrees of centralization. However, in this study only 17 system templates are applicable with the generated system options. The number of selected systems is defined by what is manageable by the decision-making process and set to one system from each template. For the selected systems we also quantified resource recovery and loss potentials for nutrients (phosphorus and nitrogen), total solids (as an indicator for energy and organics), and water. This provides the foundation to discuss trade-offs regarding different decision objectives such as resource recovery and appropriateness, with stakeholders taking into consideration their different preferences. Higher recovery ratio potentials were observed for sanitation systems with urine diversion and biogas production (ST-10 to ST-12) and the systems combining anaerobic filter and co-composting for the treatment (ST-16). The highest system appropriateness was obtained by the systems of ST-6 (ID-20), ST-9 (ID-152), and ST-15 (ID-134278). This system shows high recovery potential. The system of ST-15 (that consists of pour-flush, human-powered transport dry, solids-free sewer, anaerobic filter, co-composting, surface solids disposal, irrigation) shows the highest water recovery that is highly relevant in the water-shortage region of Lima. Safe wastewater reuse can be beneficial for communities living in the lowland (e.g., for irrigation). Agriculture is still the primary income source for communities living in Lima's peri-urban areas [20]. The system of ST-9, which is a novel container-based system, shows less water recovery, but it is a dry system and thus does not require any water input and is also resilient to floods. It makes the system particularly suitable for water-scarce areas with regular intensive rainy events [22,53]. Moreover, it simplifies the recovery of energy and nutrients from the separated urine and feces products. According to [54], the majority of Lima's informal settlements use unlined pit latrines (96%) which are only partly emptied, a small percentage discharges their toilet products to the drainage directly (3%), and only 1% of the population is considered to have safe sanitation. These pits have the potential to be upgraded with urine diversion toilets and container storage that then could be connected to a system similar to the selected system of ST-9. Similar systems have already been implemented by social ventures in Kenya and Peru [22].

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w13091197/s1, Figure S1: Histogram of sanitation system appropriateness score of all valid systems, grouped by system template and colored by the number of technologies per system. The vertical red line indicates the 90th percentile of the histogram. (SAS = sanitation system appropriateness score; ST = system template; n = total number of sanitation systems), Table S1: Summary of the case profile used as inputs, Table S2: Summary of the technology profile example used as inputs.

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