

Article

Discussion on Sustainable Water Technologies for Peri-Urban Areas of Mexico City: Balancing Urbanization and Environmental Conservation

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Abstract: Often centralized water supply, sanitation and solid waste services struggle to keep up with the rapid expansion of urban areas. The peri-urban areas are at the forefront of this expansion and it is here where decentralized technologies are increasingly being implemented. The introduction of decentralized technologies allows for the development of new opportunities that enable the recovery and reuse of resources in the form of water, nutrients and energy. This resource-oriented management of water, nutrients and energy requires a sustainable system aimed at low resource use and high recovery and reuse rates. Instead of investigating each sector separately, as has been traditionally done, this article proposes and discusses a concept that seeks to combine the in- and outflows of the different sectors, reusing water and other liberated resources where possible. This paper shows and demonstrates examples of different types of sustainable technologies that can be implemented in the peri-urban areas of Mexico City [rainwater harvesting, EcoSan and

biofiltros (small constructed wetlands), and (vermi-)composting]. An innovative participatory planning method, combining scenario development with a participatory planning workshop with key stakeholders, was applied and resulted in three concept scenarios. Specific technologies were then selected for each concept scenario that the technical feasibility and applicability was assessed. Following this, the resulting resource flows (nutrients, water and energy) were determined and analyzed. The results show that decentralized technologies not only have the potential to deliver adequate water supply, sanitation and solid waste services in peri-urban areas and lessen environmental pollution, but also can recover significant amounts of resources thereby saving costs and providing valuable inputs in, for instance, the agricultural sector. Social acceptance of the technologies and institutional cooperation, however, is key for successful implementation.

Keywords: participatory planning; resource recovery; solid waste; wastewater; water supply; decentralized technologies

1. Introduction

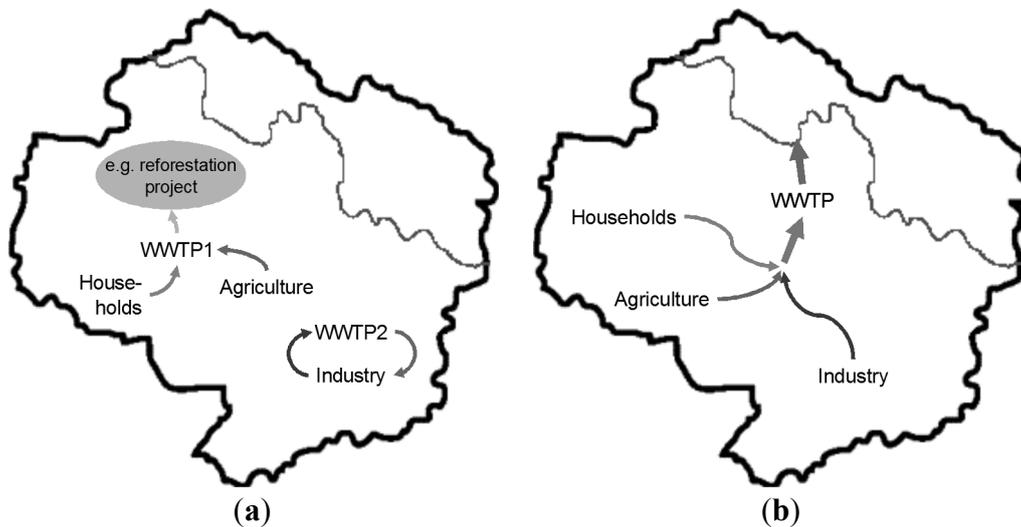
In urban and densely populated areas, centralized solutions for water management are usually favored over small scale solutions based on principles of economy of scale and economy of density [1–3]. In this traditional approach, water, wastewater and solid waste are often transported over large distances. These centralized water supply, sanitation and solid waste solutions often struggle to keep up with rapid expansion of large cities in the South, such as Mexico City, not only due to unregulated and uncontrolled urbanization, but also due to high construction costs [4]. Indeed, it is in these peri-urban areas that there is a trend towards providing water supply, sanitation and solid waste management technologies on a decentralized, on-site scale [4–8]. However, stakeholders may prefer centralized solutions because of the convenience of a centralized system.

The introduction of decentralized technologies allows for the development of new opportunities that enable the recovery and reuse of resources in the form of water, nutrients and energy. This resource-oriented management of water, nutrients and energy requires a sustainable system aimed at low resource use and high recovery and reuse rates.

Instead of designing each sector separately, which has been traditionally done, this article proposes and discusses a concept that combines the in- and outflows of the different sectors, reusing water and other liberated resources where possible, which is illustrated in Figure 1. “Joints” for possible integration of these sectors are: water reuse, nutrient recycling and energy recovery. In the decentralized concept all wastewater in a region is seen as a separate water, nutrient and energy source, and is evaluated for its suitability as a water source for a specific use, such as agriculture, non-potable domestic purposes or forest irrigation. With letting the final users determine the quantitative and qualitative water requirements needed for a specific purpose such as agriculture, industry or (non-potable) household activities, the user or purpose of the wastewater determines the quality to which the wastewater is improved, which is the opposite of the conventional water chain where governmental legislation or permits dictate the treatment level. This reverse water chain [9–11], results in a new and

novel view of waste and wastewater treatment and water sourcing where legislation should allow for tailor-made solutions. This may also reduce costs as not all waste and wastewater need to be treated up to high standards, since a part can also be used for purposes only requiring lower standards.

Figure 1. (a) Traditional way of thinking about wastewater treatment; and (b) resource oriented way of thinking on a regional scale. WWTP1 and WWTP2 can constitute completely different technologies (WWTP = Wastewater Treatment Plant).



This paper shows and demonstrates examples of different types of sustainable water technologies that can be implemented in the peri-urban areas of Mexico City. An innovative participatory planning method using a scenario building methodology at project level was applied. This method has allowed for a meaningful and intensive involvement of a variety of key stakeholders in the planning process. It also helped to identify the opportunities and limitations of resource oriented water technologies within an urban planning context highlighting the conflict between environmental conservation and urbanization.

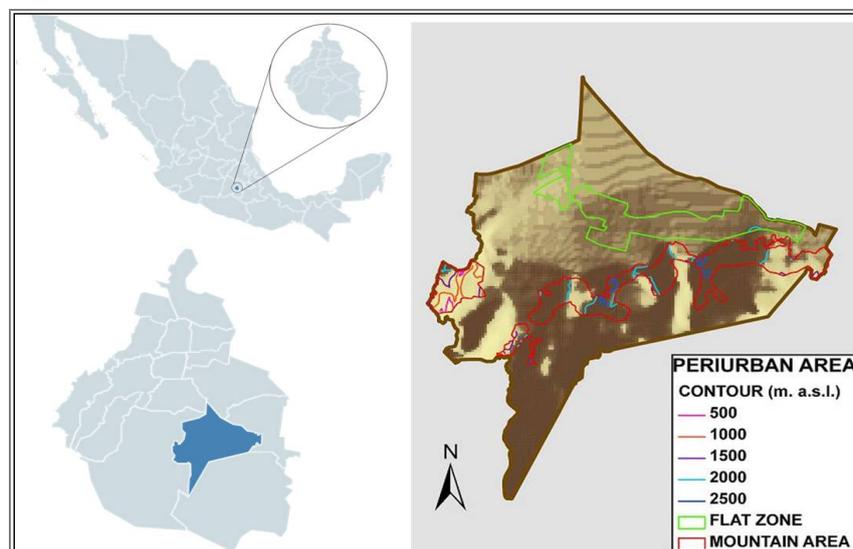
2. Case study

The case study is located in Xochimilco, one of the 16 boroughs (*delegaciones*) in Mexico City. The entire *delegación* Xochimilco has an area of approximately $12.5 \times 10^7 \text{ m}^2$ [12,13], of which $2.5 \times 10^7 \text{ m}^2$ are urbanized. The peri-urban areas (which can be legal or illegally urbanized) cover the additional $3.0 \times 10^7 \text{ m}^2$, and serve for this study (Figure 2). These peri-urban areas have a mixed topography with plain ($1.26 \times 10^7 \text{ m}^2$) as well as mountainous areas ($1.74 \times 10^7 \text{ m}^2$). Xochimilco has a high biological and cultural value due to the wetlands and *chinampas*. *Chinampas* are rectangular land plots (usually 10 by 100 meters) surrounded by narrow canals used for irrigation, fishing, transportation and as a water source. The construction of *chinampas* dates from pre-colonial times and they are used for agricultural purposes [12–15]. In general, they are considered to be biologically very diverse and agriculturally very high productive areas [12,16,17]. Farmers cultivating crops on a *chinampa* are called *chinamperos*. It was listed as a World Heritage site in 1986 and as a wetland of international importance in 2004 [12,18].

The trends of the past four decades confirm a dual-pressure process in Xochimilco, referring to progressive shortages of water and expansion of other land uses. Natural systems (water interactions,

soil, vegetation, fauna) are under pressure by the urbanization. In recent years, water has been injected into the aquifer and is used as the main water supply source to retard groundwater depletion of Mexico City. The effluent of a wastewater treatment plant, Cerro de la Estrella, is discharged to the surface water bodies of Xochimilco to ensure that water remains [12]; if this is not done, the surface water bodies will dry as the natural springs have been depleted [19]. Nevertheless, there are no signs that the drying effect on both groundwater and surface water can be countered, not to mention the environmental pollution that takes place due to the discharge of untreated wastewater by households living near or on the chinampas. If this trend continues, the expected scenario for the area is that there will be a large water deficit in the next century [20]. The peri-urban zone has been experiencing problems with services for water, wastewater and solid waste management. This situation will be aggravated due to the unregulated urbanization, definitely.

Figure 2. Case study area of Mexico City, consisting of the peri-urban zones of Xochimilco.



3. Methodology

3.1. Participatory Planning

Participatory planning is considered an important aspect for achieving sustainable water services, e.g., [21–23]. In this project an innovative approach using scenario building methodology was applied. From the wide range of available methods for scenario building, in this project we were in particular interested in those which allow the users to participate in shaping the development of their region. An example for such a method is the Future Workshop (FW) method. This method allows participants to become involved in creating their preferred future. A “classic” FW, according to Jungk and Müller [24], consists of five phases:

- (1) The preparation phase;
- (2) The critique phase;
- (3) The fantasy phase;
- (4) The implementation phase;
- (5) The follow-up phase.

In this study, the scenario workshops conducted under this study encompassed the first three phases, but can be adapted to the local needs and situation as follows:

- (1) Presentation of the overall study;
- (2) Presentation of urban problems in the case study area;
- (3) Presentation of trend analysis study;
- (4) Participants wrote what they like and what they do not like about the current situation on cards;
- (5) Elaboration of vision “Xochimilco 2030” in three mixed working groups;
- (6) Presentation of visions.

The scenario workshop aimed at the identification of different options for future regional development. Building on the outcomes of the scenario workshops, a workshop for participatory planning was conducted. This workshop focused more on the technical aspects with respect to water, wastewater and solid waste management. It encompassed two main phases: the existing environmental problems in the area were discussed; and the participants identified possible solutions and highlighted the main conflicts and barriers that need to be overcome to implement those solutions.

3.2. Development of Concept Scenarios

The results of the scenario building and the participatory planning were combined and then different concept scenarios were developed. A concept scenario encompassed a coherent set of water technologies that are suitable for a different future development scenario (e.g., urbanization or conservation). The concept scenarios were then furnished with a set of suitable technologies.

3.3. Technical Feasibility Study

Next, a feasibility was conducted which aimed at demonstrating the technical feasibility of the identified technologies for each concept scenario. As a detailed feasibility study for the entire case study area was beyond the scope of this study, a smaller area was considered much better to suit for “testing” the concepts and its technologies. For the selection, some criteria including infrastructure, urbanization, remoteness and socio-economic conditions were applied to ensure the selection is representative for most peri-urban area in Xochimilco. This included one small area in the lowland chinampa area (La Conchita) and another in the mountainous areas (San Martín). The detailed feasibility study was then conducted for each concept scenario in the selected smaller areas. The following tasks were conducted:

- (1) A detailed survey of the existing infrastructure in the case study area and a household level survey in the selected smaller areas.
- (2) A detailed technical feasibility study, which included technical design and drawings of the set of technologies within each concept scenario, thus demonstrating their technical feasibility.

3.4. Resources Flow Analysis

The flows of the different resources were analyzed qualitatively and mapped out for each concept scenario. The resources analyzed were water, Nitrogen (N), Phosphorus (P), organic matter (OM) and

energy. Then for selected technologies calculations were performed to quantify the flows. The input data used for these calculations are shown in the Tables 1–3 below:

Table 1. Amounts and composition of urine and feces [25].

Waste stream	Amount	N (g/L)	P (g/L)	K (g/L)
Urine	1.2 l/p.d	3	0.8	1.3
Feces	150 g/p.d	2	0.6	0.6

Table 2. Amount of organic solid waste and general characteristics of compost [26–28].

Waste stream	Amount	Density	N (g/L)	P (g/L)	OM (g/L)
Organic solid waste produced in Xochimilco	650 g/p.d	-	n/a	n/a	n/a
Compost	-	450 kg/m ³	3.2	0.6	120*

* Calculated from [27,28].

Table 3. Precipitation data (mm) for San Gregorio Atlapulco weather station, Xochimilco [29].

Precipitation	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Monthly sum*	13.4	14	11.7	30.7	78.6	147.9	172.2	148.7	111.4	64.2	7.8	6.6
Daily maximum	32.0	20.3	17.8	23.9	36.8	46.8	49	63.4	36.5	42.0	17.5	14.5

* Monthly sum are according to climatological normals (1971–2000) and daily maximum are observed.

The analysis and calculations not only show how (local) finite resources such as water, P and energy are recovered from waste (water), but also how they can be reused. N and OM give a clear indication of how pollution of surface water bodies can be lessened and, with P, how valuable nutrients can be recovered and reused. The analysis of the resources was grouped in water, nutrients and energy, and focused on the import and export resources as well as the generation, recovery and usage of resources within the small case study areas.

4. Results

4.1. Results—Participatory Planning

With the past and current systems in Xochimilco, natural resources have been using wastefully, continuously. The case of Xochimilco is critical for the future of whole Mexico City as it serves as a strategic water reserve for the city and for aquifer recharge. As shown in the introduction there is a strong conflict between urbanization of Xochimilco and environmental conservation, a scenario workshop was conducted regarding this background. The participants were from different stakeholder groups including chinamperos, local government representatives, NGOs and academics. The visions of the participants were similar, but could not be summarized in one single concept. Conservation of identity, which was very often mentioned during the workshop, can be partly reached by preserving water resources as they are very important part of the local culture of the chinamperos. Economy, society and the environment should be the vertices of a triangle, and have equal value. In the center of that figure may be awareness, culture and education. They could be starting points for technologies that consider also the tradition of the area and constitute an identity and culture focusing on social

justice and a balanced environment applying criteria of sustainability. The engine of these processes should be presence of and pressure from citizens: promoting the creation of new spaces and forms of citizenship or re-elaborate some of the dynamics forms of identity and space. Community-based initiatives can be more effective than public policies supported by governmental institutions, unable to sustain over several administrations.

A synthesis of the visions has shown two possible development scenarios (a development scenario is a vision of the users and stakeholders that participated in the Future Workshop on the future development of the area):

- (1) Conservation of local identity: as this aspect was mentioned very often during the workshop, a scenario which strengthens the local community was developed. It envisages local solutions and some level of engagement with the city government where inhabitants of Xochimilco are involved and participating in decision making processes concerning resource management. Water protection is a crucial component as water is highly connected to the local identity and the traditional form of cultivation in chinampas.
- (2) Economic development: This scenario builds on economic development. Originally the focus was on touristic development; however, a later refinement to the case study areas has put emphasis on agricultural development. Although the productivity of the chinampas is generally high [12], not all are used for agricultural purposes. Instead, some parts are fallow and others are used for urbanization. By protecting the chinampas from urbanization and promoting agricultural activities through capacity building and for instance new high-value crops income can increase. In addition, Xochimilco has a touristic area that could be promoted and improved. Prerequisites are a functioning water supply and sewage net, a solid waste management system and the protection of biodiversity and the natural environment that makes the area for tourists an attractive, clean destination. Local products could be certified and sold in supermarkets in Mexico City to generate higher income.

Then, a planning workshop that focused on the technical aspects related to water, wastewater and solid waste management was conducted. During the workshop participants defined various problems related to the water supply, wastewater, agriculture and solid waste for peri-urban areas in Xochimilco that they experience or perceive.

Participants acknowledge the water supply problems, including depletion of the aquifer and poor water supply services. In addition, they also indicate that the water quality, both of the environmental water as well as the domestic water, is poor, which induces several health problems. The participants perceive the discharge of poorly or un-treated wastewater to the canals, streets and environment as the main problem. This results in water pollution, loss of biodiversity and health problems. The performance of the wastewater treatment plants is perceived as being poor, both in terms of quantity and quality. The main agricultural problems are related to a lack of knowledge of farmers and the loss of agricultural land and indigenous agricultural practices such as the chinampas. The absence of solid waste classification, collection and recycling is perceived as a problem, which is mainly related to the lack of awareness about the possibilities for separating and recycling solid waste. Participants have formulated possible technical solutions to the above mentioned problems. They proposed to introduce alternative technologies for water supply, such as rainwater harvesting and groundwater recharge

systems. Filters for grey water and the installation of dry toilets could improve the situation concerning untreated wastewater discharge. For solid waste management, the initiation of a waste separation program was proposed by the participants.

4.2. Results—Concept Scenarios

Each concept scenario is related to one of the possible development scenarios and encompasses a set of technologies that is suitable for the development scenario. In addition, a new concept scenario has been created that is related to increased urbanization. Even if that was not preferred by the participants of the scenario workshop it is a very realistic scenario as a recent trend analysis based on GIS data has shown (see Figure 3). The identified three concept scenarios are summarized in Table 4.

The proposed technologies for concept scenarios 1 and 2 have a strong focus on the reuse and recycling of water, nutrients and energy. Table 5 shows examples for technologies that allow a recovery of nutrients, energy and reuse of water.

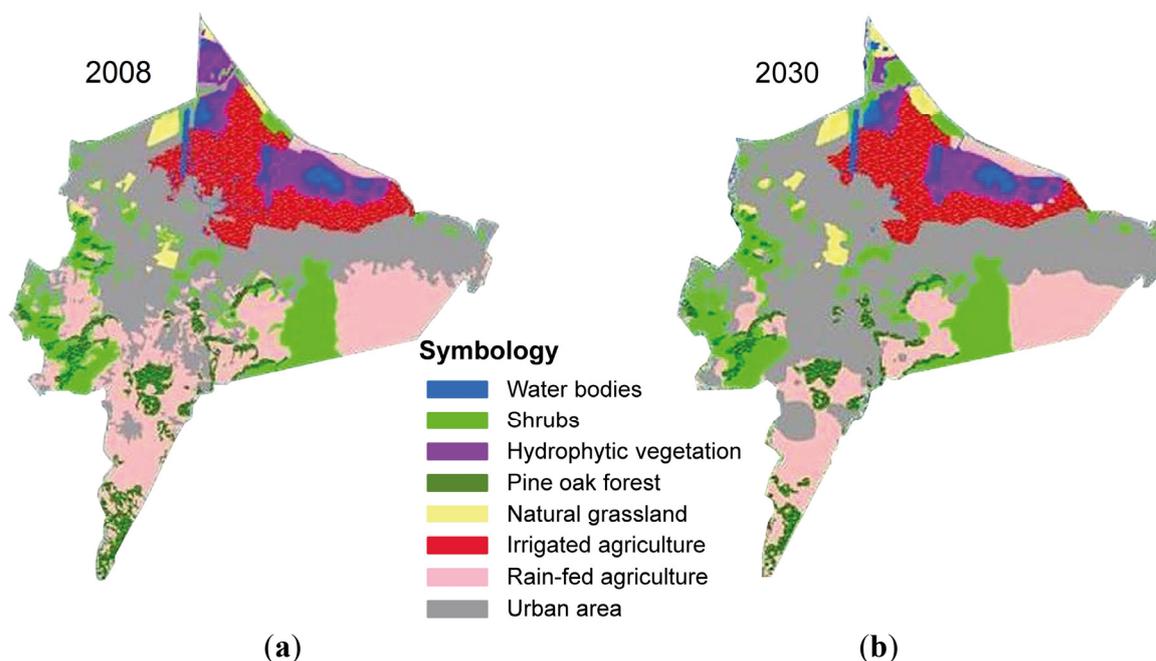
Table 4. Key objectives and characteristics of the three concept scenarios.

Scenario	Key objectives	Characteristics of technologies under this scenario
1. Local identity	The goal of this scenario is the conservation of local identity which is related to the cultivation of chinampas and the prevention of external influences.	In this concept scenario individual technical solution are preferred over centralized ones to become more independent from Mexico City.
2. Economic development	The goal of this scenario is economic development with a strong focus on agriculture. In the mountainous areas where no agriculture is practiced, there is a focus on community development.	In this scenario there is a strong emphasis on sanitation systems that allow the reuse of nutrients and the water in the chinampas or in some other areas to improve the agricultural production. In the hilly area, community technologies are the main feature of this scenario.
3. Centralization	The main goal is a strong connection to the development of Mexico City and integration into the planned urbanization.	All infrastructure services are centralized as much as possible.

Table 5. Examples for technologies with a focus on reuse and recycling.

Resource	Proposed treatment technology
Water	Rain Water Harvesting; Constructed wetlands; Compact treatment plants (e.g., Biostar); (Biological) filters to treat grey wastewater or canal water prior to use.
Energy	Anaerobic digestion of organic waste
Nutrients	EcoSan systems; Composting; Vermicomposting.

Figure 3. (a) Map of Xochimilco 2008; and (b) trend analysis for 2030 (Adapted from [30]).



4.3. Results—Technical Feasibility Study

4.3.1. Water Supply

Currently, as rainwater is the only water source not yet exploited in Xochimilco, special attention was paid to the technologies focused on this. The harvesting, storage and treatment (UV treatment, chlorination) of rainwater to supply water for households during the raining season, in combination with gabion dams that are constructed at strategic locations and thereby facilitate the infiltration of collected surface runoff, are two technologies that make optimal local use of the rainwater. The use of rainwater in the households lessens the demand for water from other sources (*i.e.*, the aquifer, surface water bodies) during a certain time of the year, and the infiltration of the remaining rainwater enables the replenishment of the aquifer and hence storage of the water for times when the water demand is higher than the available precipitation. The use of treated wastewater for non-potable domestic and agricultural purposes also lessens the demand for potable water. In general little polluted wastewaters, such as grey wastewater, can be treated by decentralized wastewater treatment systems before reuse without posing any environmental or health risks. Water from canals can also be used for specific non-potable domestic purposes such as cleaning or watering of ornamental plants. The canal water in Xochimilco is too polluted to be used directly for domestic purposes, but can be treated by for instance a constructed wetland or small water filter depending on its quality and the proposed use. Because the main precipitation in Xochimilco falls in six months (May till October), the existing centralized water supply system is expected to remain a very important source for drinking water. The conventional water supply system uses groundwater as its source, which indicates the importance of groundwater replenishment technologies. The rehabilitation and expansion of the water supply system by, for instance, legalizing the illegal connections to the water supply lines and ensuring that the existing (illegal) water pipes are properly constructed and maintained and that taps are not left to run unattended,

hence remains an important action. The following example shows how the demand for water from the centralized water supply system can be lessened through the implementation of on-site rainwater harvesting technologies with UV-treatment prior to use or consumption.

(1) Description of Current Situation

Although workshop participants have, amongst others, proposed the use of rainwater harvesting technologies (RWH) (see Section 4.1 and Table 5), at the moment these are not applied in the case study area. This can be attributed to the lack of capacity needed to construct and operate such a system, unwillingness to implement a new technology and/or the poor state of several houses. Houses in the peri-urban areas are built with a variety of materials, including cement, ceramic tiles and corrugated iron sheets, asbestos sheets, cardboard and wood. In general, inhabitants of the peri-urban areas do not pre-treat their water before consuming unless boiling. The application of tUVo's (a UV-treatment technology developed in México) and chlorination of water prior to use is currently not common.

(2) Potential Application in Case Study Area

The harvesting, storage and utilization of rainwater at domestic level is an alternative to avoid the overexploitation of the underground aquifers and the surface water sources in the peri-urban areas of the México City. This will be possible in the raining season and part of the dry season (December). The average annual precipitation in Mexico City is 807 mm [29], with the majority falling in June till October. The collected rainwater will be stored in storage tanks before use. The capacity of these storage tanks will depend on the water demand as well as if there are also connections to the centralized water supply system. As the average weekly household water demand is 0.8 m³ (with each household consisting of 4 individuals and based on households with flush toilets as well as pit latrines) a total water amount of 3.5 m³ is needed per month. In general, the roof surfaces of houses in the peri-urban areas of Xochimilco are estimated to be around 36 m² [31]. Assuming a 70% collection efficiency (losses and diversion of the first flush) 4.3 m³ of rainwater can be harvested in the month with the highest monthly precipitation (July; 172 mm) and 0.2 m³ in the month with the lowest precipitation (December; 7 mm). The highest monthly RW supply is almost equal to the monthly water demand, which means that the storage tank can be kept small as water will be used the same month it is collected. The highest daily maximum precipitation is around 63 mm, yielding a collected amount of 1.6 m³. By installing a storage tank with the minimum 1.5 m³ for each household, it is ensured that all collectable rainwater can be utilized optimally.

The installation of RWH technologies can result in the improvement of the living conditions of the inhabitants due to the improved roofs and supporting structures indirectly, and water saving directly. This will also affect the environment indirectly, as less water will be extracted from the aquifer or canals.

The installation of on-site RWH technologies will require the adaptation or improvement of houses. The main adaptations required will be new roofs and supporting structures if these are not suitable for rain water harvesting. In addition, gutters, transportation pipes and a storage tank will need to be installed. Installing the storage tank on a structure (but below the level of the roof) the water can be collected with pales or transported into the house with a pipeline. The water can be treated in the house with filtration, and/or a UV-light (a tUVo, requiring energy) or chlorination.

4.3.2. Wastewater Treatment

The use of EcoSan toilets could improve the sanitation conditions of the households and do not require water, as is the case with flush toilets, thereby lessening the overall household water demand. This is an advantage due to the current aquifer depletion taking place. Lastly, the advantage of EcoSan is that the feces and urine can be co-composted with other organic wastes or the effluents can be applied directly on the fields (chinampas or greenhouses), thereby containing resources in the area. Discharged wastewater that is not very polluted, such as grey wastewater, can be treated by constructed wetlands that can be constructed in the yards of the houses.

Another possibility is to collect the wastewater and treat it with a decentralized wastewater treatment system such as a constructed wetland. These can be constructed in gullies or drains where wastewater is collected or discharged to. Another option is to implement a more complex technology such as a Biostar, which is a biological wastewater treatment, designed by the Instituto Mexicano de Tecnología del Agua (IMTA) in Cuernavaca, México, or an Rotating Biological Contactor (RBC). However, these will need a (small) sewage network and perhaps pumps to collect and transport the wastewater besides the need for skilled operators as well as an energy source to function and perform adequately.

In a more centralized scenario the existing sewage system and wastewater treatment plant can be extended. However, the multiple unplanned settlements not only make it difficult to extend the existing sewage system in order to serve all households (as the capacity of the wastewater treatment plants might need to be increased and a new sewage network will need to be constructed amidst existing buildings and chinampas, thereby severely limiting the design possibilities), but there are also multiple buildings constructed over the existing sewage system which makes rehabilitation and extension works impossible to perform without demolishing and reconstructing the buildings. Hence the expansion of the centralized system might be more difficult to realize than the construction of decentralized measures. On the other hand, the centralized system is a technology preferred by the local inhabitants, meaning that the implementation of decentralized sanitation options might be more difficult due to the lower social acceptance. This, however, still needs to be evaluated. An example of how the implementation of a decentralized sanitation option such as EcoSan can result in resource recovery and water conservation is presented as follows:

(1) Description of Current Situation

The sanitation situation in the peri-urban areas of Xochimilco differs per location. A number of houses, generally located near the urban areas and that are connected to the water supply system or store water in tanks, make use of flush toilets. These discharge their water into the canals or septic tanks, which are often poorly constructed or just a hole in the ground. Other, more remote, households make use of pour flush toilets or pit latrines that are often poorly constructed or defecate and urinate directly in the environment. Gastronomical and skin problems and diarrheal diseases are common in these areas [32].

(2) Potential Application in Case Study Area

By constructing EcoSan toilets initially at households that currently do not have sanitation facilities or make use of pit latrines access to proper sanitation facilities is improved. The combination with a

biofiltro, which is the local name for a small constructed wetland designed to treat grey wastewater at household level, will ensure that all wastewater originating in a household is adequately treated. As it is generally the poor who do not have proper access, their livelihoods and the overall public health is impacted directly and improved. In addition, the recovery and reuse of nutrients can not only lead to less demand for artificial fertilizer (or if no fertilizer was used, higher yields), but it can also improve the soil conditions and thereby the sustainability of the land.

An EcoSan toilet can be constructed in the yard of a household, or as an extension of a house, where in general the dimensions of a toilet or pit latrine (1–1.5 m²) can be maintained. Care should be taken to design the EcoSan toilet in such a way that it uses energy from the sun to dry the collected feces. Feces and urine will be stored in two separate containers prior to their use or the co-composting. The feces and urine can be used in local gardens, greenhouses or chinampas in the form of compost. A biofiltro, with a surface area of 2 m² to treat 100 L of grey water (total dissolved oxygen demand of 555 mg/L) per day [11], can also be constructed in the yard of a house. In certain areas this is already common, and here they are constructed in the form of flowerbeds. Cases where ornamental flowers (*Zantedeschia aethiopica* and *Cannaflaccida*) are used, with good treatment results, are also known [33].

4.3.3. Solid Waste Management and Agriculture

Organic waste management and agriculture are treated in one section as the outputs of the organic waste treatment often can be used in agriculture.

Waste separation practices are considered a key practice for solid waste management. By separating the different wastes, some can be reused or recycled, while others can be used as an input for composting in order to retain nutrients in the area. If the waste is collected by a centralized organization, the inhabitants will need to store their wastes in separate closable bins till the wastes are collected. The wastes can then be recycled, composted or disposed of in a location specifically adapted to the purpose. For instance, a centralized composting plant, using vermicomposting, could treat organic wastes from an area and in turn supply the farmers of that area with a high-quality compost, soil improver or organic fertilizer. Depending on the local demand for energy, it is also possible to digest the organic wastes with manure coming from livestock to produce biogas. This can be done on household level or in a centralized way. The effluent of the biodigester can be used for fertigation and composting purposes, or organic fertilizer can be produced.

On-site composting and vermicomposting can be implemented where there is no, or very poor, waste collection facilities as the produced compost can be handled safely. These practices can also be done by families with gardens so that they can reduce their fertilizer demands. Although vermicomposting is more efficient and can eventually produce valuable side-products such as worms and proteins, it also requires more economical input (worms—*i.e.*, *Eisenia fetida*—need to be bought, a structure needs to be constructed to contain the compost) to start-up, and thus by studying both technologies local inhabitants can choose which composting type they prefer and can afford. The location of the (vermi-)composting can be in the vicinity of the house, to ease organic waste disposal, but at a large enough distance to prevent the occurrence of noxious odors or pests. The following is the presentation and discussion of vermicomposting as an example of on-site organic waste management:

(1) Description of Current Situation

The separation and recycling of solid waste is an uncommon practice in the peri-urban areas of Xochimilco. Although a number of inhabitants have access to the centralized collection service, who collect the solid waste with trucks, there are also households who do not make use of these facilities, are not or irregularly visited by the trucks or simply do not make use of the service. Hence solid waste is also burnt or discarded to the streets and environment, resulting in pollution.

(2) Potential Application in Case Study Area

The local separation of solid waste and local vermicomposting of organic solid waste will result in an overall decrease of the amount of waste to be collected. This, in turn, will lower the strain on the municipal waste collection service so that they can extend their services. Another advantage is that awareness about waste production and treatment is created with the inhabitants, making them more aware of their actions and hence less inclined to pollute the environment. Lastly, valuable nutrients are conserved and can be used in the chinampas and gardens as natural fertilizer and soil conditioners.

Vermicomposting is technologically relatively simple to conduct. It will, however, require a behavior change as solid waste will need to be separated. Also, the organic solid waste will be composted near the house, in the yard, which is something that not all households are eager to do, especially as the compost pile might need to be over-turned for active aeration. If it is done, one will need to construct a box (usually 1 m³). The composting pile will need to have a relative humidity of 70%, and an average temperature of 21 degrees Celsius for the reproduction of the worms. However, during the composting process temperatures can exceed 60 degrees Celsius, which will result in a reduction of pathogens. During (vermi-)composting in general a mass reduction of 10%–30% can be expected [34,35].

4.4. Results—Resources Flow Analysis

Based on the three concept scenarios identified during the workshop and the technologies allocated to each concept scenario resources flows were identified and calculated.

The goal of the concept scenario “Local Identity” is the conservation of local values which is related to the cultivation of chinampas and the prevention of external influences. In this concept scenario individual technical solution are preferred over centralized ones to become more independent from Mexico City.

By implementing multiple on-site technologies waste streams can be collected and treated separately (Table 6). In this concept scenario various resources flows between the sectors will take place: nutrients in the form of urine and decomposed feces as well as treated wastewater and compost will be used in agriculture. The digestion of organic waste produces biogas which is an additional local energy source. This will not only enable the recovery and reuse of water, nutrients and energy, but also lessen the demand for centralized services and hence create more independence for the users.

The objective of the concept scenario “Economic and community development” is economic development with a strong focus on agriculture. In the mountainous areas where no agriculture is practiced, there is a focus on community development. In this scenario (Table 7) the main resources

flows emanate from the sanitation systems that allow the reuse of treated wastewater in the chinampas or in some other areas to improve the agricultural production and to have better tourist services. The compost of the decentralized composting facility is used in local agriculture. In the mountainous area, community technologies are the main feature of this scenario.

Table 6. Overview of technical systems for concept scenario 1—Concept of natural resources flows.

Concept scenario 1—Local identity			
Water supply	Wastewater	Agriculture	Solid waste
- RWH (on-site and groundwater recharge)	- Separation black water/ grey water	- Conservation of chinampas	- Separation organic and inorganic waste
- Aquifer recharge through rainwater capture	- Suitable treatment for black waters (on-site treatment)	- Use of compost	- On-site (vermi)composting
- Reuse of treated wastewater for non-drinking purposes	- Treatment of grey water for reuse	- Local gardens (to support subsistence with vegetables)	- Anaerobic digestion of organic waste
- Use of treated wastewater for non-drinking purposes	- Treatment of grey water for reuse	- Use of treated wastewater	- Anaerobic digestion of organic waste

Table 7. Overview of technical systems for concept scenario 2—Concept of natural resources flows.

Concept scenario 2—Economic and community development			
Water supply	Wastewater	Agriculture	Solid waste
- Communal RWH	- Community scale wastewater treatment plant (reuse in agriculture or for non-domestic purposes)	- Reuse of water and nutrients for chinampas for agricultural production	- Separation of organic waste
- Use of treated water from channels for non-drinking purposes	- Community scale wastewater treatment plant (reuse in agriculture or for non-domestic purposes)	- Manure and other residues to composting	- Decentralized composting together with sediments from chinampas and other agricultural residues
- Use of treated water from channels for non-drinking purposes	- Community scale wastewater treatment plant (reuse in agriculture or for non-domestic purposes)	- Manure and other residues to composting	- Collection of inorganic waste, recycling and disposal

The advantage of implementing technologies on communal scale is that larger quantities of water and nutrients can be recovered at one location. Hence it is possible to reuse these resources as inputs for agriculture. In addition, side benefits, such as a business in composting, can be established. However, it is more of a challenge to separate all waste streams from the source as certain wastes have specific challenges. Urine, for example, does not allow for transportation over long distances through pipes as it can result in clogging due to precipitation of minerals (primarily Calcium and Magnesium Phosphates) [36].

In the concept scenario “Centralization” the main goal is a strong connection to the development of Mexico City and integration into the planned urbanization. All infrastructure services are centralized as much as possible.

In a centralized scenario it is much more difficult to recover resources from wastewater and solid waste (as shown in Table 8). The only resources flow between the sectors is through the organic fraction, which can be composted in a centralized location before being solid back to the farmers. The treated wastewater will be discharged to the environment.

Table 8. Overview of technical systems for concept scenario 3—Concept of natural resources flows.

Concept scenario 3—Centralisation			
Water supply	Wastewater	Agriculture	Solid waste
- Connection to centralized water supply	- Connection to centralized sewer system and treatment	- Use of compost in local gardens/agriculture	- Separation of organic waste - Centralized composting of organic waste

Examples of resources flows from earlier discussed technologies are as follows: Through the implementation of an on-site RWH system with post-treatment the inhabitants will be less depended on the centralized water supply system for their water supply. If all annual precipitation (807 mm) is collected with a 70% efficiency on the before mentioned roof surface (36 m²), this can result in a capturing of 20.3 m³, which accounts for 49% of the annual water demand of a peri-urban household not connected to the centralized water supply system (41.6 m³/year) [32].

The implementation of an EcoSan and biofiltros for the treatment of feces, urine and grey water at household level will enable the recovery of N, P and Potassium (K) as well as water. Based on data for one household the recovered amounts can be 5.7 kg N/year, 1.5 kg P/year and 2.4 kg K/year. Based on N-requirements, this is enough to cultivate 750 m² of hybrid maize capable producing 4.5 t/ha (application load of 80 tons/ha). However, if P-availability is limiting, the cultivatable area is 500 m². For K this is 300 m² [37,38]. This can deviate, depending on local conditions.

If households that currently make use of flush toilets (using an average of 7 L per flush) also construct EcoSan toilets, water can be saved. With an average of 4 inhabitants per household and 5 flushes per person per day (one flush per visit), an annual 51 m³ can be saved per household. The use of a biofiltro will ensure that little polluted wastewater can be reused in a safe way for, for instance, irrigation of crops or non-potable domestic purposes such as laundry or cleaning. The annual production of grey wastewater for a household is 112 L per household per day, which will result in an annual amount of 31 m³ of treated wastewater, assuming a 75% recovery and treatment efficiency.

The annual amount of organic waste produced per household in Xochimilco is approximately 1000 Kg. Assuming a 20% mass reduction this results in an annual production of 800 kg of compost from the organic waste of one household. The composition of compost generated will differ per location as it depends upon the organic waste that is composted, the quality of the composting facility (aeration, temperature regulation) as how the compost is maintained (moisture content and temperature). Taking the general values shown in Table 2 the amount of nutrients recovered annually by one household is 6 kg N and 1 kg P. Compost is also a source for organic matter (OM), which can be used as soil conditioner. The annual production of OM is calculated to be 200 kg OM. Based on N-requirements, this is enough to cultivate 750 m² of hybrid maize capable producing 4.5 ton/ha (application load of 80 ton/ha). However, if P-availability is limiting, the cultivatable area is approximately 300 m² [38]. Apart from the nutrients recovered through the composting process, vermicomposting also allows for the cultivation of worms that can be sold to start-up other vermicomposting sites or as protein sources for animal feeds. In one year time the amount of worms can increase by a ten-fold, and one kilogram of worms (*Eisenia fetida*) will sell for about € 15 to €60, depending on the demand and quality [39].

The different technologies as well as different resources recovered are summarized in Table 9.

Table 9. Summary of examples of on-site technologies and potential resources recovered.

Technology	Size	Potential resource recovery per household per year	Benefit
On-site rainwater harvesting with post-treatment	Roof: 36 m ² Storage tank: 1.5–2.0 m ³	Water: 20.3 m ³ (70% efficiency)	49% reduction in water demand
EcoSan and <i>biofiltro</i>	EcoSan: 1.5 m ² <i>Biofiltro</i> : 2 m ²	N: 5.7 kg P: 1.5 kg K: 2.4 kg Flush water: 51 m ³ Treated grey water: 31 m ³ (75% efficiency)	300–750 m ² of maize, producing an estimated 4.5 tons/ha Redundant flush water: 51 m ³ Recovered grey water accounts for 60% of the water demand
(Vermi-)composting	Composting structure: 1m ³	N: 6 kg P: 1 kg OM: 200 kg Worms: 10 kg from 1 kg/year	300–750 m ² of maize, producing an estimated 4.5 ton/ha

5. Discussion

The participatory planning approach combining scenario development (using a Future Workshop) with participatory planning has shown to be a useful approach to raise awareness and interest of users and stakeholders to the issues at stake. Complex technical issues could successfully be discussed with a wide range of local users and stakeholders.

When approaching the water supply, sanitation, wastewater treatment and solid waste management from the resource conservation and reuse point of view a different approach to the water chain and a different interpretation of the characteristics of the water and waste is required. By following this reverse water chain approach the potential of pollutants can be seen as valuable resources, both in terms of physical resources (nutrients or water), but also as economic resources. The brief descriptions of three different decentralized technologies show that the implementation of all three technologies can result in an improvement of the living conditions of the inhabitants of peri-urban areas while there are also economic savings as less water or fertilizers will have to be bought and one will need to pay less to a centralized body for the treatment of one's water or wastes. In addition, the individual technologies presented require little space (1–3 m²) and hence generally fit within the gardens of the local houses, even if all three are constructed at one house although this can differ per case, and can be constructed with materials available locally in México. The fact that there is no need for large excavation for pipelines or external energy sources for pumps and regulators is another technological advantage of the decentralized technologies because it increases its versatility by making it applicable for areas not easily accessible and lessens construction costs of large sewage systems.

The implementation of decentralized technologies does not by definition mean that this is on a household, or on-site, scale. If the local context allows for this, technologies could also be implemented on communal level and thereby create small economies of scale and density with all benefits (and constraints) of this. Another advantage of decentralized technologies is that different

technologies can be combined on different scales to achieve different objectives. The example presented earlier considered three specific technologies, but the research also showed that, for instance, the implementation of constructed wetlands on communal level can provide water suitable for supplementary irrigation while the digestion of organic wastes at household level provides local energy for cooking, lighting or heating. The sludge can be used as a natural fertilizer and soil conditioner, and hence an impulse to the local economy through agricultural stimulation is created.

However, as mentioned before, the implementation of the decentralized technologies and reuse of resources will require the acceptance of the technologies by society as well as a change in perception and behavior from society. In addition, it might initially cost them money as they will need to construct the different technologies. It is not self-evident that the use of collected rainwater and treatment prior to consumption (chlorine or UV-light if there is an energy source), as well as the use of treated wastewater for non-potable purposes is accepted and implemented readily by all inhabitants. Furthermore, the use of an EcoSan toilet could be perceived as less comfortable, easy or less hygienic than a conventional flush toilet. As a decentralized technology will require operation and maintenance by the inhabitant, one is directly responsible for the wastes that one produces. Hence decentralized technologies demand an active involvement of the users, for instance in the form of cleaning the roof and rainwater storage tanks, handling the (dried) feces and urine, separating wastes and periodically over-turning the compost pile. This active involvement often has a low social acceptance if there is an easier option, such as a centralized, conventional, system, available. Thus, the society plays an important role in implementing decentralized technologies as their cultural perceptions, values and wishes will need to be taken into account while designing the technology or combination of technologies, which is not self-evident [40,41].

Another obstacle for the implementation of decentralized technologies and the reuse of resources could be institutional constraints or legislation. Legislation could restrict the use of human excreta as a natural fertilizer or pose restrictions on the quality of the effluent if it is to be discharged to a natural water body. In addition, the implementation of centralized technologies can be used by authorities to gain control over resources flows to an area and hence the ability to influence its population. In the case of decentralized technologies this is much less of a possibility, and hence authorities could be less inclined to promote the approach proposed here.

The last obstacle discussed in this paper is the threat of the technologies to the public health. Although the technologies are envisaged to be implemented in peri-urban areas where there is inadequate access to safe water supply, wastewater treatment and solid waste management services, and thus improve the living conditions of the inhabitants, improper construction, operation or maintenance can result in serious health risks. This is especially the case for EcoSan, which if not constructed, operated or maintained properly can become hygienically unsafe and result in a source of pathogens or vectors, thereby increasing the risk of infections.

6. Conclusions

As the research results have shown, the implementation and combination of decentralized technologies allows for context-specific solutions to local water supply, sanitation or solid waste dilemmas that are often relevant in peri-urban areas. Moreover, it provides the opportunity to lessen

environmental pollution and recover valuable resources to sustainably improve livelihoods and the environment. However, in order to achieve this, participation of users and stakeholders is crucial. As the experiences of this project have shown, stakeholders still often favor traditional centralized solutions and, in order to facilitate the implementation of decentralized solutions, an open and transparent planning process that highlights advantages and possible disadvantages of decentralized over centralized solutions needs to be pursued. At the very beginning of such a planning process a clear vision of the local stakeholders is necessary establishing what the existing problems are and how they could be solved. A participatory planning process linked to the identification of development scenarios (using Future Workshops) as tested in this study can help to develop technical concept scenarios that show all options for problem solving. As a next step, these options need to be carefully assessed not only from an environmental, but also from an economic and social, perspective.

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