


Article

Green Infrastructure for Sanitation in Settlements in the Global South: A Narrative Review of Socio-Technical Systems

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Abstract: In the developing economies of the Global South, a fundamental challenge in the transition of settlements from rural or periurban to urban is increased environmental contamination as a result of poor sanitation and sanitation management. With governments' limited ability to connect all neighbourhoods to a city's existing municipal water, sewerage and other services, decentralised approaches using green infrastructure offer potential to address this challenge. In addition, green infrastructure might facilitate a move towards a holistic response to manage the full water cycle. This paper presents a narrative review of green infrastructure projects, involving constructed wetlands or their variants for wastewater treatment, within vulnerable communities in the Global South. It describes the scale and scope of each project, identifies the challenges of implementation, and reflects on their outcomes for different stakeholder groups. The review demonstrates that decentralised sanitation programs using constructed wetlands for wastewater treatment can provide a range of advantages/benefits/services, dependant on the specific sociocultural, political and biogeophysical contexts of each. Issues of governance and sociocultural appropriateness, rather than technical issues, challenged the implementation of green infrastructure for sanitation in these projects. Projects must be a collaboration between the government, nongovernment organisations and the community. Whether the project is organised from top-down or bottom-up, community consultation is essential. Context will determine the role of the community in the consultation process and the type of information required to guide the design, implementation and governance of the system. In every project to provide decentralised sanitation systems, the community must be participants, not simply beneficiaries.

Keywords: water sanitation and hygiene; WASH; sanitation; green infrastructure; water sensitive; wastewater treatment; Global South; decentralised; coproduction



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1. Introduction

A goal of the United Nations (UN) Millennium Declaration was to halve the proportion of people without sustainable access to safe drinking water and basic sanitation by 2015. Although the target for drinking water was reached, that for sanitation was not [1]. Approximately 2.5 billion people still had no access to improved sanitation facilities, and almost 900 million were still practising open defaecation [2]. In cities in developing countries, most communities are served by nonnetworked, on-site sanitation systems, i.e., septic tanks, cesspits, or private or public pit latrines (unsewered ('dry') toilets) [3,4]. In 2002, on-site sanitation systems were the predominant form of disposal of most urban dwellers in Africa and Asia and many in Latin America, leading to contamination of water resources and risks to public health. Problems arise when there is a mismatch between septic tank density and the soil's capacity to assimilate the waste stream, resulting in soil and groundwater contamination, and when the septic tanks, cesspits and pit latrines are not emptied frequently enough or the collected waste is disposed of without treatment [4].

Even in cities with sewerage systems, only a small proportion of the wastewater within the system is collected and the remainder is discharged to open drains or disposed of locally [5]. In 2000, the World Health Organisation (WHO) estimated that only 35% of wastewater collected by sewers is treated. The faecal sludge from these systems, often amounting to thousands of tonnes daily, is usually discharged untreated into the urban and periurban environment. The sludge might be used in agriculture or aquaculture or discharged directly into “lands, drainage ditches, onto urban spaces and into inland water, estuaries and the sea” [3] (p. 285). Consequently, water resources are contaminated—more than 880 million people rely on unclean drinking water [2]—and human health impacted. Diarrhoeal diseases kill 2.2 million people annually, including 1.6 million children under the age of five, and 10% of the population of developing countries have severe intestinal worm infections [2]. Diarrhoeal disease is the second leading cause of death in children globally [4].

The UN defines sanitation as “any safe excreta disposal that interrupts the transmission of faecal contaminants to humans” [2] (p. 649). Problems of adequate sanitation services are worsening in cities in developing countries as urban populations increase [1], and are exacerbated in informal settlements [6] and settlements in challenging environments, on marginal land or over water [7]. Sanitation coverage and levels of service are usually much lower than in formal settlements [8]. Urban planning and housing development in new areas for legal settlement in East Asia are beginning to include infrastructure considerations and, as a result, some areas are considered unsuitable for housing development because of public health risks or the high cost of providing infrastructure [7]. However, existing informal settlements might be legalised, which leads to pressure to provide sanitation, despite unsuitable locations and ground conditions, often with considerable social and technical challenges.

More attention has been given to the supply of affordable clean water than sanitation [1,7]. Once clean water is available, only then are communities interested in the provision of latrines and improved sanitation facilities. Certainly, many communities in settlements in developing countries do not understand the importance of safely managed sanitation for good health and disease prevention or the public health implications of open defaecation or fixed-point open defaecation [4,7,9].

Sanitation services must extend beyond the simple provision of toilets to meet the UN Sustainable Development Goal 6 (SDG6) of ensuring the “availability and sustainable management of water and sanitation for all” [10]; the entire sanitation system must be provided, from pre-toilet to post-toilet [11]. Traditional centralised, big-pipe sewerage infrastructure cannot easily be implemented or expanded in many settlements in developing countries for economic, spatial, social, institutional, political and informational reasons [1]. Decentralised wastewater management systems offer an alternative solution, augmenting the capacity or function of existing traditional infrastructure [12] or operating independently to provide important treatment at-source [4]. They also facilitate greater community involvement in planning, implementation and management [5]. Water sensitive approaches through the use of green infrastructure (GI) are being explored as viable decentralised wastewater treatment options, particularly in developing countries [13]. Decentralised GI offers potential to provide sanitation services in settlements in urban, periurban or rural locations.

GI is formally defined as “an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife” [14] (p. 1). This understanding has been expanded to include the use of nature-based systems as infrastructure. Given the environmental values of the location of many settlements in developing countries, GI offers “multifunctional, soft engineering alternatives to grey infrastructure, in low-income urban areas” ([6], p. 25). It also offers benefits of climate change adaptation and mitigation [6]. GI allows the integration of nature-based solutions for water into the built environment, in many cases highly modular constructed wetland systems [4]. These constructed wetlands

are a low-cost technology that can provide rudimentary treatment in the management of wastewater. Different types of wetland are available, i.e., horizontal flow, vertical flow, subsurface flow and surface flow, depending on the context of the settlement. Once treated, the effluent can be used as a resource for horticultural and agricultural production, contributing to the local economy [4,9]. In such circumstances, GI as resource-oriented sanitation [15] offers the possibility of developing a circular economy [16] in which waste products are retained within the economy as resources with value.

GI also facilitates the monitoring and evaluation of the sanitation system to determine its sustainability, which is essential to achieve UN SDG6 [17,18]. Different sustainability indices have been developed for this purpose, varying in intent, focus, scale and detail. An early index [19] assesses performance of existing systems at a city scale, focusing on environmental issues and efficiency and performance of technical systems. The Water Sanitation and Hygiene (WASH) Performance Index evaluates a country's performance in water access and equity and sanitation access and equity using UN SDG indicators and data sources from the WHO/UN Joint Monitoring Program and trends in sustainability [20]. These two performance indices can guide future progress towards sustainability. In contrast, sanitation sustainability indices can use broader sets of descriptors or subindices to characterise existing or potential systems to be implemented in cities or local communities [17,18]. The Water and Sanitation Sustainability Index (WASSI) [17] is based on a five-dimensional sustainability concept related to place, permanence and persons, and uses nine descriptors and 15 indicators, including issues of governance and customer satisfaction. It is context-specific and uses local city-based data. Another sanitation sustainability index was developed to complement the WASH Performance Index by quantifying technical, social and economic aspects of a local community. Important in this index are the acceptability and public health indicators [18]. Such sanitation sustainability indices can guide decision-making in the selection, design and implementation of a sanitation system most suitable, and hence most likely to be sustainable, in a particular context.

As most studies of GI have been conducted in cities in Europe, North America, East Asia and Australia, its relevance and practical application in a wide range of contexts are not yet established [21]. There have been few studies of GI in informal settlements, with their challenges related to urban density, informality, and land tenure. This paper attempts to address this gap, with a review of projects in settlements in low and middle income countries (LMIC) in the Global South, in which GI was implemented to provide decentralised sanitation services. We were interested in the scale and scope of the GI intervention, the challenges of implementation, and the outcomes for different stakeholder groups, especially the advantages, benefits and/or services and, conversely, the disadvantages, costs and/or disservices of these programs for each group. The focus in many papers is on the technical aspects of subsurface constructed wetlands as wastewater treatment systems. This technology has great potential for treating wastewater in small and medium-size communities because of its simplicity, reliable performance and ease of operation and maintenance [22]. The resultant effluent and byproducts can be used for irrigation, animal feed and fertiliser. In this paper, we are also interested in the social and cultural aspects associated with the implementation of these systems. As socio-technical systems, the benefits of the technology are dependent on adequate arrangements for operation and maintenance to ensure the long-term performance of the constructed wetlands, and community participation in educational programs promoting hygiene and environmental health [22]. Ultimately, we wish to establish the potential of decentralised GI for wastewater treatment in the Global South.

2. Methods

A systematic review was not undertaken for this paper, since these are best suited to narrowly defined questions involving quantitative data [23]. Despite its limitations, a narrative review format was adopted to best fulfil our intentions, allowing for a broader research question that would facilitate more comprehensive identification of issues within

a given topic from a range of literature sources [23]. The review draws on published literature identified through a structured search process of Google Scholar, using terms related to sanitation provision, including: “green infrastructure”, “nature-based systems”, “constructed wetlands”, “wetland”, “wastewater treatment”, “ecological sanitation design” and “Decentralised Wastewater Treatment Systems”(DEWATS). Searches were also conducted using the above terms in conjunction with “informal settlements”. Given that we were interested in built, rather than conceptual, projects, grey literature was also considered, including reports by implementing agencies such as the WASH program and the WHO. Additional published literature was identified through the reference lists of key articles.

Publication date was not an excluding factor, and, although no geographic restrictions were included in the searches, the literature was reviewed for relevance to urban and periurban settings in LMIC. No language restrictions were placed on the search; however, only English language documents and abstracts were reviewed. As reflected in our search terms, we were most interested in the literature related to design and implementation of sanitation systems and literature relating to built projects only was included in the review. Natural GI systems that are providing wastewater treatment by convenience—rather than by design—as can occur within the unserved informal settlement context [6,24] were not considered.

Based on the LMIC filter, our search returned projects from countries within five of the six World Bank-identified regions: East Asia and the Pacific, Latin America and the Caribbean, the Middle East and North Africa, South Asia and Sub-Saharan Africa [25]. Finally, based on data availability and the inclusion criteria defined above, 13 projects were selected. These included projects from Indonesia, Costa Rica, Nicaragua, El Salvador, Peru, Colombia, Brazil, Uganda, Pakistan, Zimbabwe, the Philippines and Nepal.

We applied a classification based on Gauss (2008), which structured project reviews under the categories: “Design and construction”, “Operation and maintenance” and “Community participation in implementation” [22]. These have been identified as important topics relating to the implementation of socio-technical systems, across literature on water, sanitation and hygiene.

3. Results

We selected for examination 13 projects in which constructed wetlands were used as GI to manage sanitation in settlements in the Global South. Descriptions of these projects differed, depending on the aim of the sanitation project and the aim of the authors in writing about it. Thus, in examining each project, direct comparisons may not be possible. Nevertheless, the critical aspects of the projects of interest in this study were the scale and scope of the intervention, and the challenges of implementation.

The scale and scope, with details of location, for each project are given in Table 1. This information was not always explicit in the description of the project and in some cases had to be inferred, indicated by a question mark. On this basis, seven projects were in periurban locations, two were rural, and four were urban. Location was not indicative of scale of operation, though. The urban constructed wetlands in Pereira, Colombia, catered for 280 people, whereas constructed wetlands in rural locations might cater for as few as four households in Santa Elena-Monteverde, Costa Rica, or as many as 5000 people in Nemanwa, Zimbabwe. Wetlands constructed in terrestrial periurban locations generally served upwards of 1000 people. In contrast, floating sanitation gardens in waterside villages in Indonesia were designed to serve two households. The preponderance of constructed wetlands in periurban locations could reflect the availability of space on the edge of cities rather than within them, for the provision of GI.

Table 1. Selected projects using green infrastructure for wastewater treatment in settlements in the Global South.

Project Name	Location	Rural/PeriUrban/Urban	Year Completed (Start-Up Date)	Number of Houses/People Serviced	Scope	Reference
BIOSANTER (Sanitation management for waterside villages)	Village of Tanjung Pagar, Banjarmasin, Indonesia	Periurban?		2 Households (8–14 people)	<ul style="list-style-type: none"> Floating toilet, biofilter tank and floating sanitation gardens as secondary treatment. Planted with water jasmine, productive crops, rice; vegetable crops. 	[26]
Reedbed	Santa Elena-Monteverde, Costa Rica	Rural	2001	4 Households	<ul style="list-style-type: none"> Reedbed system treating domestic greywater and blackwater. Flows into pond and soakage area, surplus treated water overflows to stream 	[27]
Masaya pilot plant, Reedbed ‘Biofiltro’	Masaya, Nicaragua	Periurban	(1996)	1000 people	<ul style="list-style-type: none"> Pretreatment with screen and grit tank; treatment by Imhoff tank and 4 SSHF reedbeds. Outflow used for horticulture; reedbed plants used as fodder crop. 	[22,28]
San José Las Flores	San José Las Flores, El Salvador	Periurban?	1997+ (2000)	126+ Households (650+ people)	<ul style="list-style-type: none"> Sewerage system used for most densely populated part of village (126 households). Wetland system and on-site sanitation (latrines) used for rest of population. 	[22,28]
	Lima, Peru	Periurban	2006	2500 people (three schemes)	<ul style="list-style-type: none"> Pretreatment with screen, grit separators and sedimentation tanks. Constructed wetland of 2 SSHF reedbeds. 	[22,28]
La Florida Wastewater Treatment Plant	Pereira, Colombia	Urban		280 people	<ul style="list-style-type: none"> Primary and secondary treatment via existing septic tank and anaerobic filter. SSHF constructed wetlands as tertiary treatment. 	[22,28]
	Pasto, Colombia	Periurban	2006	1000 people	<ul style="list-style-type: none"> Constructed wetland providing secondary treatment of effluent Treated wastewater used for agriculture. 	[22,29]
	Barrio of Jardim Petrolar Alagoinhas, Brazil	Periurban		2500 people	<ul style="list-style-type: none"> Constructed wetland as treatment after grit removal tank and anaerobic reactor. 	[22]
Kisoro Town EcoSan pilot project	Kisoro, Uganda	Urban	1996–1999/2000	250+ households/institutions/public facilities	<ul style="list-style-type: none"> Water-borne sanitation, sewer, constructed wetland and reuse of outflow. Combined with 3 other water-borne or dry approaches dependent on location. 	[30,31]
Machaki village	Machaki village, Pakistan	Rural	2006?	49 Households (673 people)	<ul style="list-style-type: none"> Flush toilets and greywater connected to storage tank and 2 SS constructed wetlands. Outflow used by 2 local farmers who gave land rights for system construction. 	[8]

Table 1. Cont.

Project Name	Location	Rural/PeriUrban/Urban	Year Completed (Start-Up Date)	Number of Houses/People Serviced	Scope	Reference
	Redcliff, Mupandawana and Nemanwa, Zimbabwe	Urban	1999	Redcliff: 40,000 people; Mupandawana: 250 commercial + 270 residential properties (of population, 10,000); Nemanwa: 5000 people?	<ul style="list-style-type: none"> • Duckweed pond systems, constructed wetlands and aquaculture. • Outflow reused for agriculture. • Mupandawana and Nemanwa: duckweed used in chicken feed, raising broiler chickens for human consumption. Project failed in Mupandawana. • Nemanwa: chicken droppings and dried duckweed used in vegetable gardening project. 	[28,32–34]
GK Fisherman's village	Bayawan City, Philippines	Urban		715 Households	<ul style="list-style-type: none"> • Clustered septic tanks for solid removal and VF and HF reedbeds (~2500 m²) for wastewater treatment. • Wastewater used for construction and irrigating public greens. • Sludge from septic tanks treated in central biodigester at sanitary landfill to generate biogas. 	[35,36]
Sunga Treatment System	Thimi Municipality, Kathmandu, Nepal	Periurban	2005	80 Households	<ul style="list-style-type: none"> • Pretreatment (coarse screen and grit chamber), primary treatment in anaerobic baffled reactor, hybrid constructed wetland (2 HFCWs and 2 VFCWs), and sludge drying bed. • Sludge used as fertiliser by farmers. 	[37,38]

HF, horizontal flow; VF, vertical flow; SS, subsurface; CW, constructed wetland.

As we are interested in the implementation of GI in these projects as a socio-technical system, we focused on those aspects of the system where the technology could interact with the community and might be influenced by its social and cultural aspects. Hence, each project was analysed to reveal information about:

1. Operation and maintenance (O&M)
 - Who does it and how is it financed?
 - How are the roles and responsibilities divided and what falls to communities?
2. Technical construction
 - Availability of local experience and materials—new technologies/approaches.
 - Opportunity for capacity building.
3. Sociocultural aspects
 - Contextual adaptation—based on social norms, local cultural beliefs and practices.
 - New technologies/approaches.
 - Community participation (i.e., consultation, education, coproduction, code-sign, comanagement).

The results are presented in Table 2.

The results are constrained by the information available in each project description. Nevertheless, for most we have been able to extract the relevant detail or infer it from the published material. The analysis of the results reveals that there were six approaches to the provision of GI for sanitation services in the 13 projects (Table 3). The BIOSANTER project in Indonesia is excluded from Table 3 as the data were insufficient to allocate it to a group. It was government-initiated but the extent of community involvement in consultation before the project was implemented and in management of the floating sanitation garden is unclear. In seven projects, the importance of community participation to implementation of the project was emphasised. These are highlighted in bold in Table 3. The purpose of community participation, though, differed between these seven projects, dependant on the sociocultural or biogeophysical context and needs of each. In Pakistan, Uganda and the Philippines, community participation informed the context-specific design and location of the toilets and associated infrastructure. In Alagohinas, Brazil, and Pasto, Colombia, it identified community sanitation and health priorities. In El Salvador and Nepal, it enabled the local community to operate and maintain the sanitation wastewater system, including the constructed wetlands.

Table 2. Details of operation and maintenance (O&M), technical construction and sociocultural aspects for projects in Global South.

Project Name and Location	O&M		Technical Construction			Sociocultural Aspects		
	Who Does It	How Financed	Roles and Responsibilities	Local Experience and Materials Available	Opportunity for Capacity Building	Contextual Adaptation	New Technologies/Approaches	Community Participation
BIOSANTER (Sanitation management for waterside villages), Indonesia	Property owner?			Local materials used in construction of toilet, biofilter and sanitation garden. Local aquatic productive crop plants used	Yes	Apply established technologies using locally available materials, e.g., plastic packaging, coir, coconut fibre, wood charcoal, plastic fishing nets, local aquatic plants	Innovative substitution of biofilter components with locally available materials, often waste	Not specified
Reedbed, Costa Rica	Owner of land on which reedbed is located	Environmental services contract between households using reedbed and land owner of reedbed	Responsibility for O&M falls to users and owner of system	Absence of natural wetlands; <i>Coix laryma-jobi</i> selected as emergent macrophyte-naturalised in Latin America, with deep penetrating root system	Yes	Usual wetlands species replaced with locally available wild grass	No natural wetlands due to steep topography, new technology low-cost materials and locally available plant species present opportunity	Not specified
Masaya pilot plant, Reedbed ‘Biofiltro’, Nicaragua	Well-trained local operator				Success encouraged adoption of technology in other parts of Central America	Include local fodder crop with high water and N demand, in reedbed planting. Recommended that system be fenced off to prevent theft and unauthorised entry		
San José Las Flores, El Salvador	Managed by local committee, which appointed local plant operator,	Financed by Swiss Agency for Development and Cooperation (SDC) for first 2 years. Since then, local plant operator paid by tariffs collected from community	Assistance provided initially to set up system, then users operate and manage it. System adopted for simple O&M requirements, low recurrent costs, stable treatment process and good treatment performance	Based on Masaya pilot plant in Nicaragua. System adopted because of availability of materials, stable treatment. Local operator trained at Masaya pilot plant and has trained others to fill role in his absence	Yes. Community development included in project, with financial and technical support from SDC and local NGO Pro-Vida	System copied from pilot plant in Nicaragua	Community elected Municipal Water and Environmental Sanitation Committee. Multifaceted project included community development, intensive hygiene promotion, and construction of sewerage and wetland systems. Hygiene promoters trained by NGO raised awareness of hygiene and educated villagers	Yes: “outstanding example of community participation in a sanitation project and community-based management of the sanitation system” [22] (p. 31). Citizens highly organised and motivated
Lima, Peru	SEDPAL (Lima’s water utility)	SEDPAL annual O&M budget for infrastructure maintenance	No charge to users, though separating garbage and household chemicals to facilitate function of system	Gravity-fed wetlands constructed in cut sites in steep sandy terrain. Local emergent plant species, <i>Typha domingensis</i> , used	Possibly	Local species used in reedbeds. Reedbeds are multifunctional, treating wastewater, providing green space, and operating as wind break and mitigating erosion	No natural wetlands due to steep topography; new technology and locally available plant species present opportunity	No

Table 2. Cont.

Project Name and Location	O&M		Technical Construction			Sociocultural Aspects		
	Who Does It	How Financed	Roles and Responsibilities	Local Experience and Materials Available	Opportunity for Capacity Building	Contextual Adaptation	New Technologies/Approaches	Community Participation
Pereira, Colombia	Member of local community			Technical guidance and monitoring by Universidad Tecnica de Pereira	Use of different filter media and local plants in wetland			
Pasto, Colombia	Members of local community	Jointly by Pasto municipality, local utility (EMPASTO) and NGO Semillero de Suenos			Education to enable plant management by community members			Extensive community participation and consultation to reveal community priorities for health and environmental protection, to promote hygiene, and to provide environmental education. Aim to achieve community ownership
Barrio of Jardim Petrolar Alagoinhas, Brazil	Servico Autonomo de Agua e Esgoto de Alagoinhas (SAAE, municipal water and sanitation utility)	SAAE	Environmental sanitation policy developed in participatory process with community, leading to implementation of project			Drew on experience acquired by Santa Catarina's universities in designing similar systems	Success of project attributed to participatory approach to developing environmental sanitation policy [22]	Municipality consulted with various stakeholders of community in monthly review meetings, to develop environmental sanitation policy
Kisoro Town EcoSan pilot project, Uganda	User?	Project initiated by Austrian Development Cooperation and Ugandan Directorate of Water Development	User participation important—focus of feasibility study, with local conditions	Not clear from study	Yes. Community engagement important to provide knowledge to ensure correct use of toilets and develop sense of ownership	Four components suited to local conditions: reliance on pumped groundwater, hydrogeological conditions of site (village sits above water source), poor sanitation coverage, opportunity to reuse byproducts in horticulture and agriculture.	Mix of components to adapt EcoSan system for location Decisions made on scientific and, perhaps more importantly, on social and emotional bases	Community consultation used drama, rallies and meetings to reach most community members. Political leaders gave commitment to project by implementation agreement
Machaki village, Pakistan	Government-run. Almost no running and maintenance costs.	Government funded 80% = materials transportation, construction and supervision	Pakistani convention is for government to deliver water services at minimal or no cost.	Villager contribution 20% = all raw materials for wetland construction and local labour used	Yes. Extensive community consultation to develop system consistent with cultural practices. This capacity transferable.	Adaptation of sanitation system to local religious, cultural and physical requirements, e.g., water flush.	Ecological sanitation system incorporating water flush with wastewater treatment by constructed wetlands to recover water and nutrients, used by owner of land occupied by wetland	Exhaustive and culturally sensitive community consultation and codesign. Critical involvement of religious leaders

Table 2. Cont.

Project Name and Location	O&M		Technical Construction			Sociocultural Aspects		
	Who Does It	How Financed	Roles and Responsibilities	Local Experience and Materials Available	Opportunity for Capacity Building	Contextual Adaptation	New Technologies/Approaches	Community Participation
Redcliff, Mupandawana and Nemanwa, Zimbabwe	Presumably government-run	Presumably government-funded	Water virtually free of charge in Zimbabwe	Duckweed-based ponds developed from pilot study undertaken by Zimbabwe Institute of Water and Sanitation Development	Potentially	Duckweed used as feed in chicken project to produce broilers	Chicken project successful in Nemanwa, run by youth organisation; unsuccessful in Mupandawana because of negative sociocultural attitudes to wastewater reuse.	Unclear extent of community consultation; presumably inadequate given failure of chicken project in Mupandawana
GK Fishermen's village, Bayawan City, Philippines	City government initially	City government?	O&M will be responsibility of GK Village Association after start-up	Planned and implemented with technical support of Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) Water and Sanitation Program in Philippines	Yes. Fundamental principle of GTZ	Locally available plant, "Tambo" (<i>Phragmites karka</i>), used in wetland	Wetland effluent used in construction and irrigation of public green space; sludge from septic tanks treated at central biodigester at sanitary landfill to generate gas	Implied. GK Fishermen's Village established for resettlement. Fundamental principle of GTZ activity is adaptation of system to local social-cultural context, training local participants, re-adopting, implementing, training cycle [36]
Sunga Treatment System, Thimi Municipality, Kathmandu, Nepal	Local management committee, with technical support from Environment and Public Health Organisation (ENPHO) as required. Local caretaker responsible for day-to-day O&M	Madhyapur Thimi municipality budgets for O&M and costs of caretaker	O&M undertaken by community members/users. Caretaker local community member. Local management committee to charge households nominal connection fee	Management committee chose site. Local community provided labour for construction with technical support from Water Aid/ENPHO	Yes. Members of local community developed technical and practical skills for system operation and maintenance. Management committee trained by ENPHO in book-keeping. Caretaker trained in O&M. Additional community member selected by management committee trained to provide technical support if ENPHO withdraws	Design of constructed wetland adjusted for local conditions. Emergent plants <i>Phragmites carca</i> and <i>Canna latifolia</i>	Use of anaerobic baffled reactor as pretreatment with decentralised wastewater treatment system, to reduce complexity in construction and O&M, reduce clogging by suspended solids and reduce constructed wetland sizing. Multiple uses of treated effluent, to increase environment flow of river, irrigation of gardens, and cleaning. Proposed use in agriculture, toilet flushing at school adjacent to treatment plant. Dried sludge used as fertiliser and as fuel (briquettes). Reed prunings to be available as fuel. Site of treatment plant formerly degraded. Now restored and attractive	Extensive active community participation in initiating, planning and implementing project. Community support and its pride towards project and sense of ownership identified as important to success of project

NGO, nongovernment organisation.

Table 3. Alternative approaches for provision of green infrastructure in projects. Projects in which community consultation was very important are given in bold.

Initiation	Community Consultation	Management	Project
University	No	Community	Pereira, Colombia; Nicaragua; Costa Rica
Government	No	Government	Lima, Peru; Zimbabwe
Government	Yes	Government	Brazil; Pakistan
Government + NGO	Yes	Probably community	Uganda
Government + NGO	Yes	Community	Pasto, Colombia; Philippines
NGO	Yes	Community	El Salvador
NGO + community	Yes	Community	Nepal

Design of context-specific infrastructure: Community participation in the Pakistan project was critical to an understanding of the sociocultural context of the project. In this case, sociocultural context included the community's perceptions of toilets and its cultural and religious practices and prohibitions related to defaecation, cleansing and cleanliness. This understanding was essential to ensure that the sanitation service for Machaki Village was designed to reflect its residents' values and practices and so would be used by them. Consequently, water-flushed toilets were adopted, rather than the usual dry toilets, and an underground sewerage system leading to constructed wetlands for treatment of wastewater, with water and nutrient reuse. This top-down system, in which the government provides water services, is the convention in Pakistan and an expectation. Nevertheless, in this project, the community did make an in-kind contribution to 20% of the cost. Similarly, community consultation in Kisoro, Uganda, also informed the design of the infrastructure, focused more on hydrogeological and other physical characteristics of the village rather than its residents' cultural and religious beliefs and values. The location of the village atop its only water source, soil structure and land scarcity determined the use of four sets of different components, some involving water-borne sanitation and others dry sanitation. Nevertheless, "social/emotional aspects" were considered as important, if not more so, as "rational processes" in decision-making [30] (p. 7). Effective community consultation was essential to reveal subjective responses to inform decision-making. So, too, in GK Fishermen's Village, Bayawan City, Philippines, the NGO behind the project, Deutsche Gesellschaft für Technische Zusammenarbeit, engaged in extensive community consultation to ensure that the infrastructure was best suited to the local sociocultural context. Community consultation was cyclic, involving the training of local participants, readapting, implementing, and retraining.

Identification of community sanitation and health priorities: In 2001, the Alagoinhas municipality in Brazil developed a municipal environmental sanitation policy. A participatory process between local government, the local community and the local university then followed, to develop a municipal sanitation plan for Alagoinhas. Inevitably, community priorities for health and environmental protection would have been revealed. As a result, various sanitation projects, including constructed wetlands to treat wastewater in Alagoinhas, were implemented. Community participation in Pasto, Colombia, also revealed community priorities for health and environmental protection. This participation included consultation with community leaders, hygiene promotion and environment education. One of the priorities identified was for the community to take ownership of the sanitation project and to manage it, although the local water and sanitation utility is currently managing the system [22].

Management of sanitation wastewater system: In El Salvador and Nepal, community participation was geared towards enabling the local community to assume O&M responsibilities for the project under a management committee. In both projects, the local community recognised the importance of sanitation and initiated the project, with support from NGOs. In El Salvador, the local community in San Jose Las Flores worked with the

Swiss Agency for Development and Cooperation and the local NGO Pro-Vida to implement a project based on a pilot plant successfully constructed in Masaya, Nicaragua. It elected a Municipal Water and Environmental Sanitation Committee, which promoted the project. The project involved more than a sewerage system and constructed wetlands. It included on-site sanitation for residents outside the most densely populated part of the village, community development and intensive hygiene education. The committee manages the constructed wetland system, and appointed a plant operator from the community. This person was trained at the pilot plant in Masaya, and has trained members of the local committee and a member of a local youth group to ensure continuity of operation of the system in his absence. Users of the system pay a small fee. In Nepal, the NGO Environment and Public Health Organisation (ENPHO) had introduced decentralised wastewater technology to the country in 1997. The local Sunga community in Madhyapur Thimi municipality initiated the project to manage their wastewater. With WaterAid, ENPHO worked with a management committee selected by the community, comprising 17 members representing local leaders, community-based organisations, the community, the municipality and local schools. This committee chose the site for the constructed wetland and lobbied the municipality to acquire it. The community contributed labour for construction, with technical support from ENPHO. Then the management committee assumed responsibility for the system's operation and maintenance, with a caretaker, with funding derived from an annual contribution by the municipality and from nominal connection fees from users.

The distribution of the advantages, benefits and/or services and disadvantages, costs and/or disservices in each project are shown in Table 4. In general, in these projects, residents acquired advantages, benefits and services, with few disadvantages, costs and disservices, either collectively or individually. In each case, the residents obtained sanitation services supported by a constructed wetland, reedbed or floating sanitation garden. It can be assumed that their sanitation hygiene improved and so too their health. Certainly this would be expected in those projects in which hygiene practices were promoted through community engagement activities, e.g., El Salvador. The treated wastewater was used for irrigation in horticulture or agriculture, and solid byproducts used as fertiliser or fuel. In the Philippines, biogas was generated. The amenities of the local area were enhanced by the development of constructed wetlands, restoration of local landscapes, and the provision of green space. In Lima, Peru, wind erosion was mitigated. The environmental health of nearby waterways was improved, with better water quality and increased flow. Harvested biomass from the constructed wetlands or reedbeds was used as fodder. In several projects, individual residents, as a member of the management committee, plant operator or caretaker, developed management skills. Only in four projects did residents incur any financial cost for the operation and maintenance of the sanitation system. In most of these, a community committee of management assumed responsibility for the system and charged its users (the residents) a tariff or connection fee. In general, government or municipal funding met all costs.

Table 4. Distribution of advantages, benefits and/or services and disadvantages, costs and/or disservices in each project. O&M, operation and maintenance; NGO, nongovernment organisation.

Project	Stakeholder	Advantage/Benefits/Services	Disadvantages/Costs/Disservices
BIOSANTER (Sanitation management for waterside villages), Indonesia	Resident	<ul style="list-style-type: none"> • Sanitation • Outflow used for aquatic productive crop plants in floating sanitation garden 	
Reedbed, Costa Rica	Resident	<ul style="list-style-type: none"> • Sanitation • Environmental flow 	<ul style="list-style-type: none"> • Environmental services contract between households using reedbed and land owner of reedbed • Responsible for O&M
Masaya pilot plant, Reedbed 'Biofiltro', Nicaragua	Resident	<ul style="list-style-type: none"> • Sanitation • Outflow used for horticulture; reedbed plants used as fodder crop 	
San José Las Flores, El Salvador	Resident	<ul style="list-style-type: none"> • Sanitation • Improved hygiene • Management skills 	<ul style="list-style-type: none"> • Tariff for use of system
	Local resident as plant operator		<ul style="list-style-type: none"> • O&M
	NGO		<ul style="list-style-type: none"> • Funding for first 2 years
Lima, Peru	Residents	<ul style="list-style-type: none"> • Sanitation • Green space • Windbreak • Erosion mitigation 	<ul style="list-style-type: none"> • Need to separate garbage and household chemicals to facilitate function of system
	Water utility		<ul style="list-style-type: none"> • Meets all financial costs
Pereira, Colombia	Residents	<ul style="list-style-type: none"> • Sanitation • Management skills 	
	University		<ul style="list-style-type: none"> • Ongoing technical guidance • Monitoring

Table 4. Cont.

Project	Stakeholder	Advantage/Benefits/Services	Disadvantages/Costs/Disservices
Pasto, Colombia	Residents	<ul style="list-style-type: none"> • Sanitation • Outflow used for crop production • Management skills 	
	Municipality		<ul style="list-style-type: none"> • Funding
	Utility		<ul style="list-style-type: none"> • Funding
	NGO		<ul style="list-style-type: none"> • Funding
Barrio of Jardim Petrolar Alagoinhas, Brazil	Residents	<ul style="list-style-type: none"> • Sanitation 	
	Utility		<ul style="list-style-type: none"> • Funding • O&M
Kisoro Town EcoSan pilot project, Uganda	Resident	<ul style="list-style-type: none"> • Sanitation • Byproducts used as fertiliser for agriculture and horticulture 	<ul style="list-style-type: none"> • Require knowledge for correct use of toilets
	Government		<ul style="list-style-type: none"> • Funding
	NGO		<ul style="list-style-type: none"> • Funding
Machaki village, Pakistan	Residents	<ul style="list-style-type: none"> • Sanitation 	<ul style="list-style-type: none"> • Provision of material/labour
	Owners of land used for system	<ul style="list-style-type: none"> • Outflow and nutrients used for agriculture 	<ul style="list-style-type: none"> • Loss of land to system
	Government		<ul style="list-style-type: none"> • Funding • O&M
Redcliff, Mupandawana and Nemanwa, Zimbabwe	Residents	<ul style="list-style-type: none"> • Sanitation 	
	Community groups	<ul style="list-style-type: none"> • Duckweed used for chicken feed 	
	Government		<ul style="list-style-type: none"> • Funding • O&M

Table 4. Cont.

Project	Stakeholder	Advantage/Benefits/Services	Disadvantages/Costs/Disservices
GK Fishermen's village, Bayawan City, Philippines	Residents	<ul style="list-style-type: none"> • Sanitation • Biogas * 	
	Community	<ul style="list-style-type: none"> • Green space 	
	Government		<ul style="list-style-type: none"> • Funding • O&M initially
	Village association		<ul style="list-style-type: none"> • O&M once established
Sunga Treatment System, Thimi Municipality, Kathmandu, Nepal	Residents	<ul style="list-style-type: none"> • Sanitation • Multiple uses of treated effluent, to increase environment flow of river, irrigation of gardens, and cleaning. Proposed use in agriculture, toilet flushing at school adjacent to treatment plant. • Dried sludge used as fertiliser and as fuel (briquettes). • Reed prunings to be available as fuel. • Site of treatment plant formerly degraded. Now restored and attractive 	<ul style="list-style-type: none"> • Nominal fee
	Local school	<ul style="list-style-type: none"> • Toilet flushing 	
	Community	<ul style="list-style-type: none"> • Restored landscape of treatment site 	
	Environment	<ul style="list-style-type: none"> • Increased river flow 	
	NGO		<ul style="list-style-type: none"> • Technical support
	Management committee		<ul style="list-style-type: none"> • O&M with support from NGO
	Municipality		<ul style="list-style-type: none"> • Funding

* It is unclear whether the biogas benefits the residents directly or is used elsewhere by the government.

4. Discussion and Concluding Remarks

Decentralised sanitation as GI has been implemented effectively in the 13 projects in LMIC in the Global South examined in this review. Generalisations about the best way to provide sanitation are neither possible nor desirable as context is critical in each project. An important finding has been the contextual specificity of each project and the need for a context-specific sanitation solution for each. A form of GI—a vegetated treatment system—was included in the mix of components to deliver a sanitation service, e.g., constructed wetland, floating sanitation garden or reedbed. Its exact design was determined by the political, sociocultural and biogeophysical contexts of the settlement and the availability of suitable materials and financial resources. In these socio-technical systems, the social aspect of each is as important as the technical aspect to ensure an effective system.

The uneven detail provided in each project limits their comparative analysis. However, the detail of two projects [9,37,38] and inferences from the others reveal the importance of coproduction in the design and development of the sanitation systems, their construction, O&M, and dissemination of complementary skills and knowledge, e.g., hygiene practices, to maximise the benefits of the systems. In some projects, delivery of the sanitation service was driven from the top-down, initiated, funded and implemented by the government, or by the government with support from an NGO. In other projects, it was initiated from the bottom-up, by the local community working with a level of government or an NGO. In yet another, it was initiated and implemented by a local community working with an NGO, with government funding for the construction of the system, which was then managed by the community. In each project, the specific political, biogeophysical, social and cultural contexts determined the mix of actors in the coproduction process. In all projects, however, the community was involved as active participants, not just as beneficiaries [39].

Writing about nature-based solutions for infrastructure in the Pacific, Zari (2019) emphasised that implementation demanded partnerships that embraced “community ownership, communal responsibility and creating consensus through dialogue” [39] (p. 8). Multistakeholder partnerships between governments, NGOs, and communities needed to align with customary practices. Such practices are components of a community’s sociocultural context. Thus, sociocultural context is as important as biogeophysical context in establishing how the community will contribute to coproduction. This was evident in the Pakistani project [9]. The community expectation was that the government would supply sanitation and water services at minimal or no cost. Coproduction took the form of extensive input on social and religious beliefs, values, and practices involving water and defaecation, sewage and cleanliness. The community gained ownership through the design of a sanitation system specific to their precise needs. In addition, they contributed 20% of the cost through the supply of raw materials and labour in the construction of the treatment wetland. Consensus on the best system for the community was created by extensive consultation with the community, who sought guidance from their religious leaders. Finally, communal responsibility was established by a design that reflected the religious and sociocultural practices of the community. In contrast, coproduction in the Nepalese project [37,38] was more comprehensive, with the community participating in every stage of the project. The community owned the project from the outset, initiating it with support from an NGO and local government. It is responsible for its operation and maintenance, again with support from local government. No doubt, the consensus required to achieve this was reached through extensive dialogue.

Both the Pakistan and Nepal projects demonstrate the value of communities working with government and nongovernment agencies to achieve sanitation services. Bottom-up approaches to GI without state involvement are often limited in available resources and short-lived because of the precarious living conditions of many residents in settlements in LMIC [40]. Residents have the motivation and social capacity to identify, prioritise, plan and implement projects to meet community needs, with or without government or NGO assistance, as demonstrated by the Nepal project, but they need government, NGOs or professionals to provide an enabling environment for the community-based approach to

succeed [41,42]. On their own, self-help initiatives are coping strategies only [41]. Top-down approaches are constrained by a lack of adequate material and human resources, and various ecological, institutional, political and cultural challenges [1,43]. Governments might have insufficient resources, including financial resources, to implement a long-term strategy, necessary for development of infrastructure, or they might be ineffective in their social and regulatory roles [44]. Government policy might specifically limit the provision of sanitation infrastructure to interim solutions, such as periodic waste collection and chemical toilets (usually Ventilated Improved Pits) [42]. Such limitations might result from tensions between a responsibility to service what might be regarded as informal settlements, a need to discourage their growth, and a belief that they are temporary housing solutions until residents are relocated into housing projects or the settlements are upgraded to become “formalised” [8]. Lack of space or distance from bulk water infrastructure or wastewater treatment plants might prevent centralised, sewerage systems. Local soil and hydrological regimes, e.g., high watertable, might lead to ground or surface water pollution by dense onsite greywater dispersal systems [1,4,8]. Thus, hybrid approaches involving government, NGOs and communities working together are most likely to produce sustainable sanitation solutions, which are likely to rely on decentralised systems.

Challenges still remain, however, once the system is chosen and designed. Technical challenges exist in the construction of the system, often in isolated locations with possibly difficult access to the building materials and construction skills common in the Global North. In the projects explored here, many of the local communities, working with the government or an NGO, were innovative and focused on problem solving. Western building materials were often replaced with locally available materials. For example, in the BIOSANTER floating sanitation gardens in Indonesia, local materials were used in the construction of the toilet, biofilter and floating sanitation garden, including waste in the filter medium [26]. In Nepal, the design of the constructed wetland itself was altered to fit with local conditions [37,38]. In many projects, local aquatic plants were used in the constructed wetlands, reedbeds or floating sanitation gardens [35,36] and in Costa Rica and Peru, where there were no natural wetlands, suitable local aquatic plants were chosen [22,27,28]. These aquatic plants were also productive crop plants in some projects, thereby contributing to the local community’s economic base (e.g., [28,32–34]). Once the technical system was built, governance issues had to be resolved. For example, O&M had to be arranged to ensure that the system functioned as intended and delivered the service satisfactorily. Funding for O&M had to be obtained, and also the technical and managerial skills to undertake it. Tied up with O&M are ethical issues and notions of equity [8]. Pan et al. (2015) explain that equity is “an ‘ethical concept’ related to notions of ‘social justice, fairness and human rights’, based on need as a foundation for the allocation of resources” [8] (p. 222). They add that this concept is value-laden and political, as is sustainability, and warn of a tension between meeting short-term goals and a long-term vision for sustainable and equitable sanitation services. Nevertheless, we regarded the projects here as ethical if O&M was undertaken in a way that reflected the values and beliefs of the community and the community was consulted about management expectations [43]. Eales et al. (2013) advocate for a comanagement approach, distinguishing between above-ground and below-ground activities [45]. The former, which have direct benefits to communities, are day-to-day activities such as easily detectable minor repairs and are more appropriate for community-based management. The latter, which do not benefit communities directly, are more complex maintenance works—such as desludging—and are undertaken by local government or outsourced to private partners [45]. Sociocultural context is critical here. What is regarded as ethical in Pakistan might not be ethical in Nepal. Sociocultural context and the consequent community consultation also determined the appropriate contextual adaptation of the sanitation system in each project. It was not always effective, e.g., the chicken project in Mupandawana, Zimbabwe [28,32–34]. Duckweed was to be harvested from the wastewater treatment pond for reuse as chicken feed for broilers. The failure of the project was attributed to negative sociocultural attitudes to wastewater reuse. Appropriate

community participation should have revealed such negative attitudes. Collaboration with the community must be productive to ensure “an inclusive and sustainable urban future” [40] (p. 79).

These challenges, and the ways in which they were addressed in each project, reinforce the importance of community participation in devising the sanitation project from the outset. Some of these projects are examples of “organised eclecticism” [43] (p. 15), in which there is a mix of technologies and strategies, at different scales, with different financial and governance arrangements, designed as fit-for-purpose, using both technical and socio-scientific knowledge, for the specific political, sociocultural and biogeophysical circumstances of a settlement. Oosterveer and Spaargaren (2010) describe this as a Modern Mixtures approach, which must be ecologically and institutionally sustainable, accessible, particularly for the poor, institutionally and technically feasible, resilient and robust [43]. It is not an inferior substitute, to be replaced in the future by a large-scale, highly technical centralised system but a modular approach that combines the most appropriate mix of technologies and governance options, best suited to the context. As this review has shown, selection of this mix relies on technical and sociocultural factors. Oosterveer and Spaargaren (2010) suggest that this selection should be augmented by environmental flow analysis [43].

The selection of the mix should also be informed by an understanding of the local economy and the contribution that byproducts of a sanitation system can make to establishment of a circular economy. Resource-oriented sanitation systems have the potential to generate an income for the community [15,16,46]. When the costs of an entire sanitation system, from pre-toilet to post-toilet, are calculated, including the use of treated urine and faeces as fertilizer or soil conditioner and the income from sale of agricultural, horticultural or other products derived from the system, resource-oriented sanitation systems are economically beneficial [11]. Critical to the success of this is the willingness of the local community to reuse the waste byproducts [15,46]. Traditional sociocultural practices in some countries, e.g., Korea, Japan and Vietnam, might support the use of harvested human waste for agricultural production [46]. In others, e.g., India, traditional uses of animal urine and manure provide a precedent for use of human waste, which was acceptable to about 50% of farmers in a study in Vellore. However, they preferred that their neighbours used the human waste as fertilizer and soil conditioner rather than their friends, family or colleagues [15]. Several projects in this review used treated wastewater to irrigate crops, with apparent success. The one failure involved the project in Mupandawana, Zimbabwe, in which duckweed harvested from the wastewater treatment pond was to be used as chicken feed. The potential of the sanitation system to create a resource, which could have contributed to the local economy, was lost, as was the opportunity to ensure the sustainability of the sanitation system [11]. This again highlights the importance of extensive and early consultation with all sanitation system stakeholders, including producers and consumers, in the system’s conceptualization, design and implementation [15].

The advantages, benefits and services, and conversely the disadvantages, costs and disservices, were treated collectively in this paper, mostly because of the limited detail provided in the descriptions of each project. However, various ecosystem services have been related to GI [47] and can be expected to occur as a consequence of its implementation in the projects of this study. Before the various projects were initiated, the communities would already be deriving benefits from many ecosystem services in nearby natural and seminatural areas, including local landforms, vegetation, gardens, waterscapes and agricultural areas, by virtue of their location in “ecologically significant, environmentally sensitive and/or biodiversity-rich places within cities” [6](p. 24) or through their agricultural activity. Implementation of the sanitation projects using GI would inevitably deliver more ecosystem services [6]. Diep et al. (2019) warn that problems can arise if a primary objective of the GI is to protect ecologically fragile areas, when removal of residents might be necessary [21]. However, this was not reported in any of the projects in this review.

In several projects, the supplementation of water supply by effluent was an advantage/benefit/service from implementation of the decentralised wastewater treatment.

Treated wastewater was used for environmental flows, crop irrigation and other purposes. To maximise the benefits of GI and increase the efficacy of WASH programs, CRC for Water Sensitive Cities (2017) argues that a holistic, integrated approach is essential. Acknowledging that delivering effective WASH programs is “necessarily different and more complex” [4] (p. 26) than in the Global North, they suggest that a combination of interventions that take into account context-specific social and biophysical factors at a range of scales should underpin funding policies. This aligns with the Modern Mixtures approach of Oosterveer and Spaargaren (2010), in which the entire water cycle can be managed [43]. Sinharoy et al. (2019) suggest that this might not be appropriate in all situations [1]. The provision of sanitation has lagged behind provision of water services worldwide, especially in urban areas. They suggest that it might be useful to consider them separately, “to tease out the separate challenges that have hampered the expansion of sanitation in dense urban environments” [1] (p. 6). The conclusion, of course, demonstrated by this narrative review, is that every community differs and the appropriate WASH service and its cobenefits must be unique, determined by political, biogeophysical and sociocultural contexts. A holistic approach might be the solution in one location but not another. Nevertheless, GI has great potential to contribute to WASH programs in the Global South. However, careful planning and comprehensive community participation with government and nongovernment entities are essential to determine the right socio-technical system for the right place.

More information is required to fully understand the success of the projects examined in this review, in particular relating to acceptance of the byproducts from the wastewater treatment for use, the methods of community consultation, and the hygiene education programs implemented for community members. In addition, it would be interesting to determine the sustainability of each system by applying a sustainable sanitation index, and to determine the contribution of the systems to establishing a circular economy for each community. These offer potential for further studies.

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