

## Review Paper

### A review of sanitation technologies for flood-prone areas

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#### ABSTRACT

Despite the formal acknowledgment of sanitation as a fundamental human right, more than 600 million people still practice open defecation, most of them in poor countries. A part of this challenge is related to the type of natural environment such as floodable areas where flooding affects thousands of people every year and has a direct impact on their access to sanitation. Although there is a wide range of technological sanitation options for vulnerable communities, few publications explore their applicability to areas prone to constant natural floods, thereby hampering the possibilities for improving sanitation conditions in such areas. This review aims at compiling and consolidating current information on sanitation options for floodable areas with a focus on their technological, environmental, and managerial peculiarities. A systematic review identified 28 relevant publications presenting sanitation solutions for those environments. They were grouped into dry solutions and wet solutions. Our analysis showed that there is no single universal technology capable of solving the problem but instead, a set of different technological arrangements that could be implemented bearing in mind the environmental and social contexts in which they are inserted.

**Key words** | feces management, floodplain, wastewater, wetland

#### HIGHLIGHTS

- Information compiled on sanitation technologies specific to floodable areas.
- Non-technological aspects about sanitation technologies that are important for its management.
- The article may contribute to the academic community and practitioners who work with sanitation in flooded areas.

#### INTRODUCTION

A decade ago the United Nations organization acknowledged the right to sanitation as a basic human right for the full enjoyment of life ([United Nations General Assembly 2010](#)) and reaffirmed that it is the duty of the state to commit to the progressive implementation of that right by means of government

efforts that include the implementation of the appropriate legal measures ([United Nations General Assembly 2011](#)).

Since then considerable improvements have been achieved in the coverage of sanitation worldwide. In the period from 2010 to 2017, there was a worldwide reduction from 21 to 9% in open defecation. Even so, 672 million people still continued to practice it ([UNICEF & WHO 2019](#)).

There are various reasons for the occurrence of open defecation and among them are socialization habits among

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residents, convenience, religious beliefs, toilet hygiene and maintenance drawbacks, family and community norms concerning latrine use, lack of privacy for women, lack of latrines in the household, geographic location, schooling levels, water availability, family size, residential infrastructure, ethnic group of the family, land availability, type of soil, and others (O'Connell 2014; Abubakar 2018; Bhatt *et al.* 2019).

In addition to those challenges, the local environmental conditions can be limiting factors for the implementation of a sanitation technology, especially in areas that are subject to natural flooding (Djonoputro *et al.* 2010; Mamun & Monirul 2012). Wetlands and floodable areas cover almost 10% of the planet's surface (Tockner *et al.* 2008) and are effectively complex environments for sanitation solutions, given the variations in water levels they are subject to, which may submerge extensive areas to a greater or lesser depth.

Countries whose populations are impacted by flooding include Bangladesh (Ministry of Environment and Forest (MOEF) 2009; Shimi *et al.* 2010; Islam 2012), Brazil (Ramalho *et al.* 2009), China (Zhang *et al.* 2002; Huo-Po *et al.* 2013), India (Mohapatra & Singh 2003), Pakistan (Tariq & Van de Giesen 2012) and Vietnam (Bich *et al.* 2011; Chau *et al.* 2013). In those countries alone, there are an estimated 13.5 million people affected by river floods (Ward *et al.* 2013).

Floodable areas are considered to be among the most productive in the world (Junk *et al.* 2010; Pettit *et al.* 2011), and hence, their intense human occupation to exploit their natural resources (Queiroz & Peralta 2010). At the same time, however, the absence of sanitation technologies suitable for floodable environments has a negative impact on residents' health, with diarrheal diseases (Levy *et al.* 2016; Prüss-Ustün *et al.* 2019) mainly affecting poor people and especially those in rural areas (Horwitz *et al.* 2012; Parvin *et al.* 2016).

Small-scale or 'on-site' sanitation technologies can be considered the most suitable for rural environments with low population densities (Paterson *et al.* 2007), because they are simple, readily accessible, easier to design, and more liable to be socio-culturally acceptable (Mara 2003). Furthermore, they are beneficial in places where there is a lack of government commitment (Green & Ho 2005), especially taking into account the indirect savings related to reduced healthcare costs arising from investments in water and sanitation (WHO 2014).

Scientific publications regarding on-site sanitation technologies published in recent years reveal a variety of options including water-based solutions, urine diversion toilets (Rieck & Muench 2011), composting toilets (Berger 2011), and ecological sanitation (Ecosan) (Hu *et al.* 2016), all of which have great potential for application in rural communities. Other documents present detailed technical information on various sanitation solutions, describing their applicability and the pros and cons of their utilization (Tilley *et al.* 2014).

In spite of all the solutions presented in the scientific and technical literature, a systematic approach to floodable areas and publications specifically focussing on them are comparatively scarce in the literature. There is a notable lack of more in-depth studies on this theme and of elements revealing the technological and management specificities that are necessary for sanitation in flood-prone areas. That dearth of information constitutes a knowledge gap and a challenge to be faced by communities living in such areas and by the institutions that are involved in sanitation. These include, not only public institutions, whose functions include establishing public sanitation policies, but also research institutions and various non-governmental organizations (NGOs) that dedicate themselves to sanitation in floodable areas and also contribute to those policies.

This review aims to highlight the existence of that gap and contribute towards the production of systematic studies for flood-prone areas, compiling information on sanitation technology for these areas, with a special emphasis on the technological, environmental, and managerial peculiarities that make it possible to apply them in those environments.

The original incentive for the development of this paper was the need to obtain supporting information for the sanitation of floodable areas in the Amazon region, which covers a substantial percentage of the surface of the planet. However, the concepts and information obtained by this review may be also considered applicable to naturally flooded areas in other regions of the world.

## METHODOLOGY

### Search method

For the purposes of this review, we considered scientific articles, review articles, and grey literature discussing or

proposing technological solutions for sanitation in floodable environments. No restrictions on the date of publication were imposed for the search, and only articles published in English were considered. Grey literature was included in order to broaden the scope of the publications searched and because it includes important technical and scientific case studies and technical guides.

### Searching the databases

Search strings were applied to the following scientific databases: British Library, Cochrane Library, Google Scholar, IWA Publishing, JSTOR, Periódicos Capes, Practical Action Publishing, ProQuest, PubMed, Research Gate, Scielo, ScienceDirect, Scopus and Web of Science. The sources of grey literature of institutions that are involved in sanitation were: Community-Led Total Sanitation ([www.communityledtotalsanitation.org](http://www.communityledtotalsanitation.org)), Plan International, Sustainable Sanitation Alliance (SuSanA), Water and Sanitation Program Library, WHO – Iris and World Bank Publications. Further searches were made in relevant titles in the digital library of the research group the authors belong to.

Key terms related to the theme of ‘sanitation’ were paired with key terms associated with floodable environments, searching the titles or abstracts for any of the following associations: ecosan OR latrine OR sanitation OR septic tank OR sewage OR toilet AND flood OR floodplain OR flood-prone OR monsoon OR varzea OR wetlands. The pairing process resulted in 36 combinations.

In addition, in order to identify review papers that might contain indications regarding technological options for floodable areas, we searched the titles alone for the following combinations: sanitation AND technology AND review. Thus, the search involved 37 combinations altogether (Figure 1 in Supplementary Material).

### Study selection

The results of the database search were set out in an electronic spreadsheet and duplicated titles were then removed. The remaining titles were evaluated independently.

At that stage of selection of the relevant titles, the criterion used was the presence at least one of the key terms

in the title. Following that we proceeded to read the abstracts of the remaining publications to assess their relevance for the proposed objective of the review. The criterion used to evaluate the abstracts was the presence of information on sanitation technology for floodable areas or of a list of sanitation technologies. Those abstracts that failed to meet that criterion were removed from the list of studies.

Following that stage, we analyzed the texts of 66 publications to verify their contents and their compatibility with the study objective. As a result, some studies were discarded either because they lacked sufficient information on sanitation technology or because they were not relevant. By the end of the selection process, 2,272 titles had been analyzed and 28 included in the present review (Figure 2 in the Supplementary Material).

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## FLOODABLE ENVIRONMENTS

Floodable areas such as coastal areas and estuaries, swamps and high groundwater areas, and areas prone to regular flooding are highly challenging environments for the implementation of technological sanitation solutions (Djonoputro *et al.* 2010), considering that the latter are almost always buried in or supported by the soil which is subject to the flooding process.

Given their relevance for the present discussion, it is important to understand the various natural flooding phenomena and relate them to the possible sanitation solutions. Literature reports the following phenomena: flash floods, tidal floods, monsoon floods, rainwater floods and river floods (Tockner *et al.* 2008; Doswell 2015). Each one of them is associated with its own range of water-level variation and the period of occurrence (Table 1).

Flash floods caused by storms may last as long as 2 weeks and usually achieve a level of 75 cm above the soil surface (Kazi 2003). With a similar amplitude, tidal floods occur every day and can flood to a depth of around 1 m above the soil surface (Mulyani *et al.* 2017). Longer lasting phenomena are more common in flood plains where the high-water period may be as long as 3 months as in the case of the monsoon floods or even 4 months in the case of river floods. The amplitude of floods can attain extreme levels as in the case of the Amazon River floodplains,

**Table 1** | Types of natural floods and implications for sanitation

Types of natural floods	Characteristics and challenges for sanitation	Examples	Water level above the soil	Flood time	References
Flash flood	Of sudden occurrence and short duration, caused by local storms. Due to their unpredictability, they represent a serious challenge for sanitation and make its installation planning and maintenance very difficult.	Bangladesh	0.15–0.75 m	2–15 days	Kazi (2003); Doswell (2015)
Tidal flood	Flood caused by the tide. Both amplitude and duration are predictable. Saltwater corrosion and constant erosion processes jeopardize toilet substructures. Constant flooding jeopardizes sewage networks and interrupts service provision.	Indonesia Philippines	Up to 1 m	Daily	Djonoputro <i>et al.</i> (2010); Mulyani <i>et al.</i> (2017)
Monsoon flood	The summer monsoons are usually associated with very intense rainfall. Flooding from monsoons is similar to rainwater flooding. Although it occurs at a predictable time of the year, its amplitude is unpredictable and it is capable of causing catastrophes. In this last case, it tends to jeopardize any sanitation systems in place (latrines or sewage networks).	India Pakistan	0.3–0.6 cm Variable	3 months 3 months	Mohapatra & Singh (2003); Andersson (2012); Tariq & Van de Giesen (2012)
Rainwater flood	Similar to a flash flood, but less intense. Occurs in specific areas that are subject to heavy rainfall. Its impact is related to the impermeability of the soil. It leads to flooding of latrines in soil with poor drainage. Commonly occurs in floodplains.	Bangladesh	Variable	Variable	Kazi (2003)
River flood	Flooding associated with the seasonal rise in the level of the rivers. As it occurs in a known period of the year, it is relatively predictable. However, the great amplitude of the variation in the level makes toilet construction difficult as they need to be installed at extraordinary high levels. Other challenges are the collapse of riverbanks and an increase in open defecation due to the long period the flood persists. It is an important phenomenon in floodplains.	Bangladesh Brazil-Amazon Cambodia	Up to 3.5 m Up to 10 m Up to 9 m	2–4 months 3 months Variable	Balzer & Pon (2003); Ramalho <i>et al.</i> (2009); Islam (2012); Borges Pedro <i>et al.</i> (2018)

where the water level may vary by up to 10 m (Ramalho *et al.* 2009) and in Cambodia, 9 m (Balzer & Pon 2003).

## APPLICABLE TECHNOLOGIES FOR SANITATION

Altogether we identified 21 sanitation technologies suitable for flooded areas (Table 2) and they could be grouped under the

headings of ‘Dry Solutions and Water Flush Solutions’. All of them are considered as being ‘safely managed’, as they are non-shared solutions and the excreta are, at least theoretically, disposed of in a safe manner (WHO/UNICEF 2017).

It must be stated that the solutions identified are not exactly technological innovations specifically for floodable areas, but instead, adaptations of consolidated solutions susceptible to being applied in such environments.

**Table 2** | Sanitation technologies for flood-prone areas

Group	Sanitation technologies recommend for flood-prone areas	Level of application	Cost	References
A. Dry solutions	1. Biodegradable bags/Peepoo	H	•	FANSA <i>et al.</i> (2011); Bastable & Lamb (2012); Spit (2014)
	2. Composting toilets (including floating variation)	H	•	Anand & Apul (2014); Spit (2014)
	3. Dehydration vaults	H	••	Biplob <i>et al.</i> (2011); Khan <i>et al.</i> (2012); Tilley <i>et al.</i> (2014)
	4. Elevated Pit Latrine (including Earth Stabilized or Mound Latrine)	H	••	Kazi (2003); Morshed & Sobhan (2010); Bastable & Lamb (2012)
	5. Elevated Movable Plastic Drum System	H	•••	Khan <i>et al.</i> (2012)
	6. Floatable system – Rottebehalter	H/N	••	Spit (2014)
	7. Raised Fossa Alternata	H	•	Spit (2014)
	8. Sand Enveloped Raised Pit Latrine	H	••	Kazi (2003)
	9. Step Latrine	H	••	Kazi (2003); Mamani Ronteltap & Maessen (2014)
	10. Twin Pit with Urine Diversion	H	•	Khan <i>et al.</i> (2012); Spit (2014)
	11. UDDT (including floating variation)	H	•	Morshed & Sobhan (2010); Hagan & Brown (2011); Sayre & Sayre (2011); Bastable & Lamb (2012); Guadagni (2012); Hagan <i>et al.</i> (2012); Uddin <i>et al.</i> (2013); Spit (2014); Gomes <i>et al.</i> (2015)
B. Water flush solutions	12. Combined pit latrine	N	••	Morshed & Sobhan (2010)
	13. Constructed wetlands system	H/N	•••	Allen (2015)
	14. Conventional flush toilet + biogas	N	•••	Mamani <i>et al.</i> (2014)
	15. Floatable system – Biodigester	H/N	•••	Hughes (2011)
	16. Floatable system – BIOSANTER (Bio Sanitation Floating)	H/N	••	Sumidjan (2015)
	17. Floatable system – Floating pods (with or without fish)	H/N	••	Spit (2014)
	18. Raised septic tank	H/N	••	Spit (2014); Tilley <i>et al.</i> (2014)
	19. Septic tank + post treatment	H/N	••	Borges Pedro <i>et al.</i> (2011); Mamani <i>et al.</i> (2014); Silva <i>et al.</i> (2017); Borges Pedro (2018)
	20. Single plastic drum system	H	•	Mamani <i>et al.</i> (2014)
	21. UDDT + biogas plant	H/N	•••	Khan <i>et al.</i> (2012)

H, household; N, neighbourhood; •, low; ••, medium; •••, High.

The main adaptation being proposed in the relevant publications is the elevation of the entire treatment system, so that it is situated beyond the reach of the floodwaters and can function properly. In field trials of various different technological options, the raised options have consistently proved to be more suitable (Morshed & Sobhan 2010) and more acceptable to their users. Some of the names of sanitation technologies testify to their adaptation via elevation: Elevated Pit Latrine, Elevated Movable Plastic Drum System, Raised Fossa Alternata, Sand Enveloped Raised Pit Latrine, and Raised Septic Tank. Furthermore, we observed that other nomenclatures adopted in the selected literature did not refer exclusively to the treatment of excreta, but

focussed on the sanitation interface: Step Latrine, Conventional Flush Toilet, and Single Plastic Drum System.

Figure 3 in the Supplementary Material presents a short description and simple schematic drawings of the main technologies mentioned here and helps to get a unified view of the technologies.

### Dry solutions

The solutions that come under this heading are usually low-cost set-ups, and their application is generally associated with low-income countries where the target populations are vulnerable (Mara & Evans 2013). The simplest toilet

option technology in this group is the Peepoo bags, a low-cost, low-maintenance solution accessible to all populations (Vinnerås *et al.* 2009).

Another characteristic of this group of technologies is present in the Ecosan approach which focusses on the possibility of using the sanitation by-products (feces and urine) in agriculture, addressing the process as a nutrient cycle. Furthermore, it is a technique that does not need water to operate (Winblad & Simpson-Hébert 2004). One of the repeatedly recommended options among the technological alternatives of the Ecosan group is the Urine-Diverting Dehydrating Toilet (UDDT) (Uddin 2011) applied in flood situations with 100 units installed in Bangladesh (Menter 2016) and 575 in Mozambique (Fogde *et al.* 2011). There is a variant of the UDDTs consisting of floating units whose concept and design are the same as the regular ones but applicable in communities where the residents live in floating houses on rivers or lakes (Hagan *et al.* 2012). Although they are recommended in various publications for the context of high-water seasons, there are restrictions on their use associated with the aspects of maintenance (feces handling), smell, and acceptance by the users (Mkhize *et al.* 2017).

Pit latrines appear as a technological option with various nomenclatures according to the variations in their forms of construction, structure stabilization, and access to their superstructure. They are as follows: Elevated Pit Latrine (including Earth Stabilized or Mound Latrine), Sand Enveloped Raised Pit Latrine, and Step Latrine. In all of them, the excreta treatment unit (the pit) consists of a set of concrete rings one on top of the other up to a height sufficient to ensure that the superstructure is higher than the maximum high-water level and thereby guaranteeing its proper functioning (Kazi 2003). Earth Stabilized Latrines require greater areas for their construction due to the stabilization of the raised pit with the earth surrounding it. The Mound Latrine is similar to the Pit Latrine but requires a smaller area for the construction of the pit which may be formed by concrete rings and is also stabilized by the mound of earth surrounding it. The difference between the two is not clear in the literature, although they are presented as being options distinct from one another (Kazi & Rahman 1999). The author of this report considers them to be one of the best options for the floodable areas of Bangladesh.

The design of the technological option Sand Enveloped Raised Pit Latrine is focussed on preventing the

contamination of drinking water sources. There is a recommendation that a 500 mm thick layer of sand should be spread on the ground around the pit and that it should be at a distance of at least 10 m from any source of drinking water. As in all the above options, concrete rings elevate the squatting slab with stabilization with soil to ensure that the high water does not jeopardize the use of the toilet and stabilization is achieved using soil (Kazi 2003).

The construction of the Step Latrine is based on the same principle as the other pit latrines. It is set on concrete rings at a height higher than the maximum high-water level and its external surface is made impermeable. What distinguishes it is the fact of making the outer surfaces of the concrete rings impermeable, given that there is no soil available for stabilization, and also the fact that access to the toilet is up a set of steps (Kazi & Rahman 1999).

Another option the literature identifies is Dehydration Vaults. The nomenclature of this technology is based on the way the excreta are treated and its interface requires the installation of a Urine-Diverting Dry Toilet (UDDT) to obtain the separation of the urine from the feces. It consists of chambers or Vaults that foster the dehydration of the feces. The vaults need to be watertight to avoid the penetration of external humidity. With those characteristics, they are sufficiently resistant to be used in floodable areas (Tilley *et al.* 2014). Part of the Ecosan line of technologies, the dehydration vaults make it possible to use the feces and the urine in crops, so it is an attractive option for family farmers (Biplob *et al.* 2011).

The literature also indicates Composting Toilets for use in floodable areas (Anand & Apul 2014). They are treatment units made up of a composting chamber where human excreta are converted into compost. Due to the need for a suitable degree of humidity, the urine and feces need to be separated and that is usually achieved through the installation of a UDDT (Tilley *et al.* 2014) which is characteristic of the Ecosan approach. Natural or mechanical ventilation may be required to obtain the best results. In the latter case, electricity supply must be available (Berger 2011).

### Water flush solutions

The main feature of these solutions is that they require water to transport the excreta to some form of treatment unit by means of cistern flush or pour flush toilets. The hydric seal

with which they are provided generally ensures odour control and makes it less perceptible. The water needed for flushing the toilet can be surface water, rainwater, or grey water (Tilley *et al.* 2014). Research carried out among rural communities in the Amazon region (Gomes *et al.* 2015) and in South Africa (Mkhize 2017) has shown that users find the water flush toilets more desirable as they associate some degree of social status to their use and also find them easier to maintain and clean than dry solutions.

Constructed Wetlands have also been suggested as a solution for floodable areas of Cambodia (Allen 2015). In spite of the lack of more detailed technical information (horizontal or vertical, post-treatment), some advantages have been reported, such as not requiring the use of electricity or chemical products, minimal operational requirements, aesthetic acceptability, and expected high efficiency in removing *Escherichia coli*.

Designed for floating houses, Floatable System – Floating Pods (with or without fish) are small tanks attached to the residential toilet that receives the raw sewage. The tanks are planted with water hyacinth (*Eichhornia crassipes*), and the contaminants are stabilized around the rhizomes of the plants so that the effluent becomes significantly clearer (Spit 2014). According to the published material, the system is capable of eliminating smell altogether. A variation of the system used in permanently flooded situations has fish present in it.

Again for floating residences, there are the Floatable System – Biodigester – and the Floatable System – BIOSANTER (Bio Sanitation Floating). According to Sumidjan (2015), the former system was at the stage of being developed and adapted for use in floating communities in Cambodia by local institutions with biodigester expertise (Hughes 2011). The BIOSANTER is a biological treatment for sewage that consists of a sedimentation tank, known as the BIOFIL, followed by a Constructed Wetland planted with an ornamental species (*Rechinodorus paleaefolius*) and using support materials such as wood and coconut fibre (Sumidjan 2015). The system is on a scale that enables it to serve 12 persons and results show good BOD removal efficiencies, well within Cambodia's legally acceptable parameters.

In addition to those floating options, we identified two other solutions involving biogas generation using biodigesters: the Conventional Flush Toilet + Biodigester, and the

UDDT + Biogas Plant. The first is a relatively simple solution and consists of a conventional toilet with a water flush, a device with water seal (toilet seat or squatting), and a ferro-cement reactor to store feces, with the top of the reactor in a concave shape and the entry point low down on the side. The entire system is gas proof and high enough to ensure that the point of entry is above the maximum flood water level. To stabilize the structure, it is constructed with an earthen mound. The system is costly and therefore considered not feasible for low-income families (Mamani *et al.* 2014).

Septic tanks were also identified as solutions for floodable areas, and indeed, they are among the most commonly found water-based solutions. The adaptations needed to make them feasible in flood-prone areas are their elevation to a height that avoids the entrance of water in the system (Spit 2014). To ensure the best possible quality of final effluent, they may be conjugated with a post-treatment such as a constructed wetland or an anaerobic filter (Borges Pedro 2018).

## Comparison of the technological solutions

Table 2 presents a listing of the technologies, with a classification of their application (household or neighbourhood) and relative costs. Unfortunately, the consulted literature did not allow a systematic comparison in terms of removal efficiencies of the main pollutants of interest in floodable areas, especially pathogenic organisms.

Sanitation solutions should be adopted based on a broad view that encompasses aspects related to their financial, environmental, social, technological, and management sustainability. The literature describes several indicators that could be considered in sanitation projects with a view to verifying their sustainability, as compiled in Table 3.

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## OPERATION AND MAINTENANCE

Of the 28 texts included for analysis in this review, only 10 presented any information regarding management aspects, such as operation and maintenance (Uddin 2011; Sanyal & Aid 2011; Uddin *et al.* 2013; Anand & Apul 2014; Tilley *et al.* 2014; Allen 2015), use and cleaning (Biplob *et al.* 2011;

**Table 3** | Sustainability indicators for sanitation solutions

Criteria	Indicators
Environmental	Technological and social adaptation to the environment, environmental security (avoiding contamination)
Financial	Accessible costs, population's willingness to invest
Management	Ease of construction, sub-product management (sludge, feces, and urine), operation and maintenance simplicity, well-defined management systems, local and regional government roles in management, monitoring by local government, and other institutions of interest
Social	Acceptability for target population, convenience, safety
Technological	Performance, durability, replicability, scalability, technological improvement capacity, resistance to floods/droughts/rains, robustness, appropriate materials

Sources: Kvarnström *et al.* (2004); Djonoputro *et al.* (2010); Taylor (2013); Mamani *et al.* (2014).

Uddin 2011; Sanyal & Aid 2011; Uddin *et al.* 2013; Anand & Apul 2014; Tilley *et al.* 2014), sludge management (Sanyal & Aid 2011; Anand & Apul 2014; Tilley *et al.* 2014), and gender sensitivity (Guadagni 2012; Hagan *et al.* 2012).

However, those publications did not present in-depth discussions of specific aspects that take into account, for example, who is responsible for the operation and maintenance, what precautions are necessary to extend the useful life of the technology while maintaining its efficiency, maintenance costs, and how the flood-prone environment may have an impact on the respective information. Given the importance of these latter aspects that lie outside the scope of the publications included in this study, it was found necessary to have recourse to additional complementary bibliographic sources, which are summarized in Table 4.

Each technological arrangement has its own peculiarities and, according to the environment where the technology is intended to be installed, those specificities may or may not be advantageous. All the arrangements, however, can be adapted for installation in floodable areas, provided that a prior environmental study is carried out, examining all the aspects cited in Table 4 before selecting the most suitable technological design.

## NON-TECHNOLOGICAL ASPECTS – MANAGEMENT ISSUES

Technology per se is not sufficient to guarantee the success of a sanitation solution. It is considered that social aspects are essential and, if not adequately taken into account, failure of the implemented solution is likely to occur. This section covers some of these important elements.

### Gender and sanitation

Gender inequality is a worldwide problem and present in all aspects of social life. The differences between men and women and their implications are mirrored in the access, management, and benefits brought by water supply, sanitation, and hygiene (Heller 2016).

In low- and middle-income countries, there are problems associated with difficulty in accessing water and sanitation as, for example, psychosocial stress (Wutich & Ragsdale 2008; Stevenson *et al.* 2012) and risk and fear of violence, aggression, or rape (Abrahams *et al.* 2006; COHRE *et al.* 2008; Lennon 2011; Massey 2011).

Generally, it is women who are responsible for various tasks associated with sanitation, such as cleaning latrines, making water available for the toilets, taking care of their children when they use the latrines, and other everyday chores, especially in developing countries (Kuria *et al.* 2005; Münch *et al.* 2012).

From the technological standpoint, projects should be gender-sensitive and offer solutions for safe access to appropriate installations, taking into account the basic needs of all the different age groups (Wendland *et al.* 2012; Münch *et al.* 2012; Tilley *et al.* 2013). From the management point of view, it is important to ensure that women have the same power of decision in the processes as men and that their experiences and demands are heard and taken into consideration (GWTF 2006).

In areas prone to flooding, women face similar problems to those in non-floodable areas. During the flood season, women reduce their food and drink intakes to reduce the frequency of going to the toilet, because in a flooded area it is hard to find a safe and comfortable spot, especially for elderly women. During the dry season, women may face limited availability of water for personal hygiene. This limits the number of times women can wash themselves and bathe,

**Table 4** | General information on technical management aspects of the technologies, by groups

Groups <sup>a</sup>	Technological arrangement	Excreta handling	Sludge (treatment)	Use and cleaning	Odour	Emptying	Specific management aspects for floodable areas
Pit latrines	4. Elevated Pit Latrine 8. Sand Enveloped Raised Pit Latrine 9. Step Latrine 12. Combined Pit Latrine	Only in the case of composting to produce fertilizer	Can be buried, composted or Arborloo system (Still 2002; Morgan 2008) can be used	Only in the case of water flush toilets	Use of sand, soil, sawdust, and similar materials	Use of MAPET (Muller & Rijnsburger 1994), or Gulper (Ideas at Work 2007) manual pumps, or hiring latrine-emptying service (Still 2002)	Emptying should be done before flood water reaches the pit
Ecological sanitation	2. Composting toilets 3. Dehydration Vaults 5. Elevated Movable Plastic Drum System 6. Floatable system – Rottebehaelter 7. Raised Fosse Alterna 11. UDDT	Yes, for fertilizer production (Rieck & Muench 2011) Also necessary to eliminate odour (Spit 2014; Tilley <i>et al.</i> 2014)	No sludge produced	No water needed	Use of sand, soil, dry leaves, sawdust, and frequent manipulation of feces	Done manually and feces should be stored for a 6-month sanitization period	For floating communities, there is a floating sewage station that collects stores and treats excreta allowing for their posterior in agriculture after the flood recedes (Hagan & Brown 2011)
Settling chambers	13. Constructed Wetlands System 16. Floatable system – BIOSANTER 17. Floatable System – Floating pods 18. Raised Septic 19. Septic Tank + post treatment Tank 20. Single Plastic Drum System	Not necessary	Can be done as described for pit latrines (manual or mechanical desludging + burying, or sewer plant or composting)	Chlorine or detergent-based products must not be used (Silva Marmo & Leonel 2017)	Controlled by means of hydraulic seal	Emptied at intervals of 2–5 years (Still 2002; Tilley <i>et al.</i> 2014)	Should be built on a raised base to keep tubes and connections beyond the reach of flood waters
Biodigesters	14. Conventional flush toilet + biogas 15. Floatable system – Biodigester 21. UDDT + biogas plant	Not necessary	Depending on use, disinfecting may be necessary	Chlorine or detergent-based products must not be used	Little or none	From 5 to 10 years, depending on the frequency of use and the number of users (Tilley <i>et al.</i> 2014)	Avoid contact of tubes and connections with flood waters

<sup>a</sup>Technologies have been grouped according to their design similarities to facilitate the discussion. Individual technologies are numbered according to their numbers in Table 2.

adding to their discomfort, especially during menstruation (UNDP 2006).

### Community participation

Those who will be users of the proposed sanitation solutions should participate right from the planning stage of actions designed to implement the toilets. By and large, the available technologies have been presented in community projects with the involvement, to a greater or lesser extent, of the users in the decision regarding the most appropriate option for the local reality, including aspects of the toilet interfaces and their adjustment to existing needs (Tumwaze & Mosler 2014). There are studies that have identified how participation in the selection process (Goodwin 2016) optimizes the population's appropriation of the sanitation technique.

The participatory construction process makes it possible for information related to solution use and maintenance to be identified at opportune moments, raising awareness among users regarding their essential role in ensuring the proper functioning of the technique (Hendriksen *et al.* 2012). The involvement of the families during the planning and implementation of toilets has shown itself to be an important facilitator of the acceptance and appropriation of the toilets (Kazi 2003; Kiba *et al.* 2011; Gomes *et al.* 2015).

### Social acceptability

Another important factor in determining the sustainability of a given technology is its acceptance by the local community (Simms *et al.* 2005; Zhou *et al.* 2018). It is important to analyse users' reactions in regard to the way the technologies are planned and implemented (Tilley *et al.* 2013), because that stage is when their perception of the risks and the benefits become crucial for their acceptance of the technology (Hurlimann 2007; Weisenfeld & Ott 2011; van Dijk *et al.* 2017). The public's assessment and perception of the benefits that the technology offers are also an indicator of acceptance (Poortvliet *et al.* 2018).

It may be helpful to use criteria to verify whether a technology is being socially accepted. Factors that could serve as criteria are: safety during use, privacy, comfort, simplified maintenance, resistance to the weather, adaptability to

floods, interest in by-products, good appearance, guarantee of social status, prestige, and honour (Mazeau 2009; O'Connell 2014).

Two main factors tend to be involved in the non-acceptance of toilets: the smell and the manipulation of the feces (Jorritsma *et al.* 2009b). The smell is usually associated with environmental contamination and the risk of catching diseases (Sarmiento 2001; Knudsen *et al.* 2008), which makes the possibility of having to live with the smell one of the main obstacles for the families to overcome (Rheinländer *et al.* 2013). Toilets that require constant contact with the urine and the feces for their maintenance are less acceptable because it is a task that most users prefer not to perform even if it means having to stop using the toilet (Mkhize *et al.* 2017). The simplified maintenance of the toilet is considered to be a tool that facilitates user acceptance (Diallo *et al.* 2007; Roma *et al.* 2010); there is a direct connection between maintenance and acceptance (Mkhize 2017). Other factors associated with social unacceptability are a lack of gender sensitivity (non-participation of women) and the costs involved in construction (Jorritsma *et al.* 2009a).

The literature review has demonstrated the importance of achieving social acceptance for the implementation of sanitation technologies. To achieve a good degree of acceptance, the technology needs to satisfy certain criteria regarding sanitation technology established by social consensus such as smell, maintenance, gender sensitivity, and low cost.

### Flood and health impact

Flood periods are commonly related to health risks, with direct or indirect consequences. Direct ones are those in which they occur due to direct contact with water and the flooded environment, such as drowning, different injuries, and chemical contamination. Indirect consequences are those whose damage is indirectly caused by water to the natural built environment, including displaced populations, malnutrition, and infectious diseases (Du *et al.* 2010).

Infectious diseases play an important role in the discussion on sanitation and floodable environments. Floods can compromise water supply infrastructure and sewage treatment systems (large scale) or latrines (small scale), especially in rural areas, where providers' resources and

experience are limited. In the period of drought, after flooding, inadequate sanitation solutions allow effluent to drain over the soil surface, providing the formation of excreta film on the surface and a pulse of pathogens when new rains occur (Levy *et al.* 2016).

All these mechanisms will depend on the lentic or lotic conditions that prevail in the water environment. In any case, there is a compromise in the quality and quantity of safe water to the population, increasing the risk of communicable diseases, such as waterborne and vector-borne disease (WMO 2015).

Among the main diseases related to floods are cholera, typhoid fever, leptospirosis, and Hepatitis A, as well as the risk of diarrhoea caused by enteric pathogens such as *E. coli*, *Campylobacter*, *Cryptosporidium parvum*, *Cyclospora*, *Giardia*, *Norovirus*, and *Rotavirus* (WHO 2011; Alderman *et al.* 2012).

The main recommendations to mitigate the harmful effects of floods are: (a) to discourage open defecation; (b) allow people to use their own latrines as a priority; and (c) use of improved sanitation systems, which are designed to reduce the risk of contamination, such as Pit latrine with slab, Flush/pour pit latrine, Ventilated improved pit latrine, Ecological toilet, and Septic tank. For these technologies, it is recommended to raise its structure to guarantee its full functioning during the flood, according to literature guidelines (Morshed & Sobhan 2010).

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## FINAL CONSIDERATIONS

During the analysis of the relevant publications, we observed that the main focus was on dry solutions in the ambit of ecological sanitation for the re-use of the sub-products in agriculture. Usually, those solutions were indicated for poor farming communities in developing countries like Brazil, Bangladesh, and Cambodia.

The available publications addressing the topics of sanitation and technology do not present sufficient technical information to enable an understanding of the specificities that would be necessary to implement them in the challenging environments addressed in this study. Even so, it identified 21 technologies that show technological potential for solving sanitation problems that exist for communities in flood-prone areas. Another aspect that the literature does not explore or provide information on is the role of the

national or regional governments in the management of technologies which leaves a wide gap regarding the responsibilities of the actors involved in sanitation.

This survey has led us to believe that there is no single solution for sanitation in floodable areas in a universal technology perspective but instead, there are different technological arrangements whose implementation processes need to take into account the social and environmental contexts in which they are to be inserted.

Given that the proposed sanitation solutions are for vulnerable populations, it is imperative that there should be social participation in the planning and implementation processes. The desires, anxieties, opinions, and traditional knowledge of the beneficiary users must also be part of the process to ensure the success of sustained use. Solutions that require complicated maintenance (and that are associated with taboos, such as the need to handle feces) are not always acceptable by the communities.

## Recommendations

Based on the survey made and the gaps identified, we recommend research be conducted and duly communicated on specific technological development frameworks for floodable areas, to gain an understanding of the technological performances of sanitation solutions in flooded environments. Also, further research on social approaches capable of interpreting user's appropriation of the solutions is necessary. We consider that institutions involved in sanitation must direct their efforts at the elaboration and dissemination of protocols with the complete information on the process of implementing sanitation technologies for floodable areas.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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