



Costs, Climate and Contamination: Three Drivers for Citywide Sanitation Investment Decisions

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Significant progress is needed, in both large cities and small towns, to meet the ambitious targets set at international and national levels relating to universal access to safely managed sanitation. There has been increased recognition in the urban sanitation sector that in rapidly growing cities, there is unlikely to be a single centralized sanitation solution which can effectively deliver services to all demographics, and that heterogeneous approaches to urban sanitation are required. At the same time, due to competing investment priorities, there is a greater focus on the need for sanitation investments to address multiple objectives. However, calls for more informed sanitation planning and a more dynamic and disaggregated approach to the delivery and management of sanitation services have had limited impacts. This is in part due to the complexity of the drivers for sanitation investment, and the difficulties involved in identifying and addressing these multiple, often conflicting, goals. This paper examines three potential drivers of citywide sanitation decision-making – public health, sustainability and economic performance – via the three proxies of contamination, climate change and costs. It examines the importance of each driver and proxies, how they are considered in investment decisions, the current state of knowledge about them, and priority aspects to be included in decisions. At present, while public health is a common driver for improving sanitation, there are significant gaps in our understanding of fecal contamination spread and exposure, and how to select sanitation solutions which can best address them. Climate change is sometimes seen as a low priority for the sanitation sector given the immediacy and scale of existing challenges and the uncertainty of future climate predictions. However, potential risks are significant, and uninformed decisions may result in greater costs and increased inequalities. Cost data are sparse and unreliable, and it is challenging to build robust cost-effectiveness analyses. Yet these are needed to compare citywide options based on least-cost over their full life cycle. This paper provides insights into how existing evidence on contamination, climate change and costs can inform decisions on sanitation investments and help chart a sustainable way forward for achieving citywide services.

Keywords: urban sanitation, decision-making, contamination, climate change, cost-effectiveness, wastewater, sustainability

INTRODUCTION

The re-emergence of a citywide perspective on sanitation has focused much-needed attention on sustainable solutions that consider the full sanitation service chain for the entire urban population. This perspective echoes many earlier calls for a radical shift from business as usual to address the inequalities, inadequate coverage and sustainability issues of current poor sanitation in many low- and middle-income countries (LMICs) (e.g., Kalbermatten et al., 1982; Wright, 1997). Globally, one billion people in urban areas are without even basic access to sanitation, considered a basic human right, and inequalities persist, with an increasing gap in access between the richest and poorest urban households in 30% of countries (UNICEF and WHO, 2019). An estimated 53% of the global urban population does not have safely managed sanitation (UNICEF and WHO, 2019), reflecting numerous failures across the service chain and resulting in the discharge of untreated fecal waste across the urban environment (Peal et al., 2014). This situation disproportionately affects poor and marginalized groups (UNICEF and WHO, 2019).

Urban sanitation specialists have long recognized that to achieve citywide sanitation there needs to be a shift away from fixed conventional sanitation technologies toward planning approaches that incorporate a range of solutions to address sanitation in ways which are disaggregated, both geographically across the city and along the sanitation value chain (Wright, 1997; BMGF et al., 2017). Yet the persistent focus of technicians and investors on centralized sewerage systems has resulted in investments concentrating on small, often wealthier, areas of cities, with low-income and challenging areas left with sub-standard services (McGranahan, 2015). Illustrating this point, a recent assessment of the outcomes of investment by development banks found that between 2010 and 2017, banks invested 20 times more in sewerage than in fecal sludge management (FSM) despite the much larger populations serviced by onsite systems (Hutchings et al., 2018). While FSM has received growing attention, onsite and centralized options are often considered independently of each other, without an understanding that combined solutions are the likely way forward in most cities (Hawkins et al., 2013). There is a growing consensus that achieving 'sanitation for all' requires a mix of different contextualized solutions that embrace various scales of technologies and services (Lüthi and Sankara, 2018), and that inequalities in exposure to fecal waste must be actively monitored and progressively reduced (UNICEF and WHO, 2019).

Shifting from business as usual requires improved decision-making frameworks to assist in selecting appropriate investments that balance economic, public health and environmental objectives (WHO, 2018). While these three overarching objectives are often said to drive sanitation investment, it is not always clear how the options considered will contribute to achieving each objective (Kennedy-Walker et al., 2014). In many cases, competing or interlinked objectives are brushed over or only briefly considered. For example, even

economic performance, which is usually explicitly examined in development bank operations, is rarely used to compare and prioritize different sanitation delivery options. It is even rarer to see an explicit discussion of the relative importance, for example, of public health, economic performance and sustainability when sanitation options are being prioritized. This is in part due to the lack of requisite data and the absence of institutions with the ability to balance multiple, often conflicting, drivers of investment.

To illustrate the challenges and opportunities inherent in moving toward a more nuanced approach to decision-making, this paper examines contamination, climate and costs as critical lenses for considering the public health, sustainability and economic dimensions of citywide sanitation. These three areas were identified as traditional and emerging drivers that in practice are not being adequately addressed in decisions on citywide sanitation. While investment decision-makers may recognize the importance of these three areas, they may fail to consider them for a number of reasons, including: uncertainty about how to practically include different drivers in option comparisons (fecal contamination, climate), the low priority they assign to these drivers (climate, at times fecal contamination), and inconsistent or limited data and approaches for analysis (costs, contamination). As detailed in the following sections, recent publications have also identified contamination, climate and costs as requiring greater attention. The World Health Organisation (WHO) has reaffirmed that widespread fecal contamination, particularly in low-income urban areas, means that the public health objective for sanitation requires renewed attention (WHO, 2018). Various authors (World Bank, 2011; Oates et al., 2014; ISF-UTS and SNV, 2019; UN Water, 2019; WHO, 2019) have called for climate resilience to become an integral part of decision-making frameworks and implementation approaches. Finally, a recent review of the costs of urban sanitation highlights data gaps in cost reporting and life cycle costings (Daudey, 2018) pointing to inadequate attention to this dimension. This article extends existing analyses by synthesizing a broad set of recent literature and identifying how the three drivers may be better considered when developing citywide services.

This paper reviews the English language literature and draw on both academic literature as well as high-quality gray literature, predominantly published in the last five years, found through systematic literature searches of titles, abstracts and keywords including sanitation and any of: decision-making; planning; options; climate; public health; pathogens; costing; or finance. We discuss each of the three areas in terms of its significance to urban sanitation, the state of knowledge and knowledge gaps, the extent to which it is currently considered in decision-making, and priorities for increasing the attention given to each issue. Recognizing the challenge of balancing these multiple drivers, we also identify interconnections between contamination, climate change and costs, and the implications of these connections for achieving the overarching objectives of sustainable, equitable citywide sanitation.

CONTAMINATION

Given the central aim for sanitation to prevent human exposure to disease, and the wide evidence base concerning the burden of disease related to poor sanitation (Freeman et al., 2017; Prüss-Ustün et al., 2014 and Pullan et al., 2014), this section argues for greater consideration of fecal contamination in sanitation decision-making. Although health has previously been an incentive for prioritizing sanitation, there is little evidence that health is central to long-run investment planning for sanitation in many LMICs (Cummings et al., 2016). The health and economic impacts of poor sanitation are often poorly understood and “invisible,” so sanitation tends to be seen as a technical engineering task undertaken in formal areas of a city (Cummings et al., 2016). Indeed, mainstream approaches to the planning and design of sanitation systems reflect this framing, and typically focus on the protection of downstream waterways by instituting environmental discharge standards, often without explicit consideration of pathogen removal (Mills et al., 2018). Even when discharge standards exist; their enforcement is limited and political will is needed to regulate and enforce pollution control measures (UN Water, 2017; WHO and UN Habitat, 2018). Whilst chemical contamination, for example by nitrates, heavy metals and other emerging contaminants, is relevant for public health (Cronin et al., 2007; WHO, 2015; UN Water, 2017), in this paper focus on fecal contamination. This is because of its significance for achieving genuinely ‘safely managed’ citywide sanitation in LMICs, as demanded by the Sustainable Development Goals (SDGs), and also because it acts as a useful proxy for the effectiveness of urban sanitation systems in interrupting transmission pathways for infectious excreta-related diseases.

Understanding fecal pathogen contamination in urban areas is particularly important in cities and towns with low levels of effective sanitation infrastructure and services. Low levels of access to sanitation are associated with an increased prevalence of disease, particularly diseases that continue to inflict a heavy burden in low-income settings, including diarrhea, soil-transmitted helminth infections, trachoma, cholera and schistosomiasis (Speich et al., 2016; Freeman et al., 2017). In locations with high prevalence rates of infectious disease, pathogen concentrations discharged to sanitation systems or into the environment are correspondingly high, particularly during outbreaks (Lusk et al., 2014). The risk to human health is not only driven by pathogen occurrence but also by their persistence in the environment, the presence of vectors or intermediate hosts, and the level of infectivity of individual pathogens (Aw, 2018). In addition, several diseases such as pathogenic *E. Coli*, salmonellae, and shigella have low infectious doses (e.g., can cause infection in humans with fewer than 20 organisms), whilst they are present in much higher concentrations in wastewater (e.g., more than 10,000 organisms/L) (Lusk et al., 2014). Pathogens that are discharged across the urban environment can be transmitted through multiple exposure pathways, including through contact with drain water, surface water or flood water during activities such as playing, washing and bathing, and through food pathways (Wang et al., 2017). When assessing the potential risks associated

with different sanitation systems in decision-making, these numerous exposure pathways and high persistence must be considered. There is limited information about the relative importance (in terms of hazard and exposure) of the multiple sources of fecal waste discharged to the environment across the sanitation chain (for example from open defecation, overflowing pits, discharge of effluent to drains or dumping of sludge). A clear understanding of existing knowledge and knowledge gaps is critical, and in this section we review the status of knowledge related to different sanitation systems and approaches to assessing risks.

On-site sanitation systems are the dominant type of sanitation in urban areas in low- and middle-income countries (UNICEF and WHO, 2019). Confusion abounds regarding definitions of onsite sanitation systems. Key distinctions are frequently conflated. In relation to contamination, the main distinction is between lined tanks and partially lined tanks that are effectively sealed (often erroneously described as ‘septic tanks’), and systems which are designed for infiltration of liquid fractions into the ground surrounding the tank.

Starting with septic tanks and sealed tanks that are often described as septic tanks, WHO (2006) note that pathogen removal in septic tanks is poor. Authors variously suggest a treatment effectiveness of 0–2 log removal of pathogens, with several suggesting 0.5 log removal (Feachem et al., 1983; Stenström et al., 2011). As such, septic tanks alone are not considered to be a significant barrier against pathogen transmission, and it is recommended that they discharge to a properly designed and sited soil absorption system (Adegoke and Stenstrom, 2019). Adegoke and Stenstrom (2019) research also notes that treatment effectiveness assumes that the septic tank is operating as it is designed to, that it has at least two chambers and that it is regularly emptied of sludge to ensure adequate hydraulic retention time. Often these conditions are not met, and in these cases treatment effectiveness is unknown. WHO (2018) suggests that poorly designed or constructed onsite systems are not expected to reduce the likelihood or severity of exposure to hazardous events. Large numbers of such sealed tanks discharge directly to surface water bodies and drains, resulting in a direct risk of exposure (Peal et al., 2014). In addition, most studies examining pathogen removal from septic tanks have been conducted in high income countries where high water use and connection of both blackwater and graywater to sanitation systems result in lower pathogen concentrations than those typically seen in LMICs. One factor compounding misperceptions by sector practitioners about pathogen removal is that removal is often reported arithmetically rather than using logarithmic scales, which are more appropriate when dealing with large numbers. This can mask the high numbers of excreted pathogens that remain after primary onsite treatment. For example 99% pathogen removal is equivalent to 2 log removal, so with excreted pathogen concentrations potentially 9–10 log, after 99% removal the effluent may still contain 7 log pathogen concentrations (Mitchell et al., 2016).

Overall, there is a paucity of literature on the fate of pathogens in effluent from onsite systems as it enters the environment (e.g., into soil, groundwater, drains, etc.) and the

magnitude of related public health risks (WHO, 2018). Despite this, current mainstream approaches to improving sanitation in LMIC frequently focus on emptying and treatment of fecal sludge, with more limited attention given to the construction quality of onsite and offsite systems and to the pathways the liquid portion of the waste may take in an urban environment (Mitchell et al., 2016; Peal et al., 2014). Further, while there is known variation in the fate of different pathogen types (including viruses, bacteria, protozoa and helminths) in onsite systems and the environment given their different sizes, properties and characteristics (Mitchell et al., 2016), there is limited information available on their relative inactivation and persistence under different environmental conditions (Murphy, 2017). Finally, there is a knowledge gap regarding the partitioning of different pathogen types between the sludge and effluent in onsite systems.

With minimal pathogen removal in onsite systems, the effluent presents significant risks to health. We discuss this firstly from a groundwater contamination perspective, and then from the perspective of surface water and drains. Recent WHO (2018) design guidelines require that wet pit latrines only be used in areas of deep groundwater, and that if groundwater is used for domestic water supply then: pits should be located at least 1.5 m above the water table; 15 m horizontally down-gradient from the water supply; no graywater should be added; and septic tanks should discharge to a soak pit or leach field. However, appropriately designed soak-aways and absorption trenches are typically missing in dense urban areas or may be used in unfavorable groundwater conditions (high water table, highly porous soils) (World Bank, 2015; Peal et al., 2020). In addition, research has found that the travel distance of pathogens varies widely, questioning the validity of generalized separation guidance between pits and wells (Williams and Overbo, 2015). Recent studies in the United States have shown that the number of septic tanks in an area has a significant influence on the level of human fecal pollution in groundwater (Sowah et al., 2017). There are also concerns that pathogens from pit latrines can reach groundwater of varying depths, with a review of the existing literature noting that viruses in particular can travel long distances. Whereas protozoa and helminths could be expected to be retained by the soil beneath pits (Orner et al., 2018), viruses have been found in groundwater tube wells up to 50 m away from toilets (Verheyen et al., 2009). However, most research relating to the contamination of groundwater tube wells fails to distinguish between contamination from toilets via the groundwater and direct contamination of the tube wells from the surface. The significance of groundwater contamination will vary by city. Importantly, contamination of shallow groundwater from non-toilet sources is usually high, and in general the use of shallow groundwater for urban water supplies is not recommended, though its use is a reality in many contexts. In some locations where piped water is available, both fecal and other contamination may be a minor consideration. In other contexts, for instance in Indonesia where 32% of the two lowest quintiles in urban areas use on-premises self-supplied groundwater (BPS, 2018), such contamination may be a cause for concern, requiring the application of related tools to assist in risk assessment (e.g., see SanitContam in Krishnan,

2011). However, it is worth mentioning here that the complete replacement of sanitation systems that rely on leaching (to avoid fecal contamination of the surface environment) may need to be weighed up against options for water supply improvements to reduce groundwater use.

Where infiltrating pit soak-aways or leach fields are impractical, there is little evidence of the widespread adoption of safe alternatives (which would primarily focus on either the provision of solid-free sewage to convey liquid effluent to treatment, or the adoption of alternative technologies such as sewerage or container-based sanitation). The most common approach is to discharge pits and tanks directly to water bodies or open ground. In many locations, discharge from septic tanks or pit latrines to drains or waterways presents a significant hazard; often there is inadequate space for a soak pit or the groundwater level is too high to permit infiltration. The Sanitation and Health Guidelines (WHO, 2018) consider any containment units, including septic tanks, that are connected to a drain or a water body are unsafe due to the exposure hazard of the effluent. Despite this, at present the management of liquid waste from containment systems is not included in common FSM solutions and diagrams (see Parkinson et al., 2014; Strande et al., 2014) and insufficient consideration is given to the health risks of onsite systems in dense urban areas (Satterthwaite et al., 2015). WHO (2018) argues that there is currently a lack of options for improving containment and reducing the exposure to effluent from onsite systems discharged to open drains. Indeed, it is highly probable that additional effluent conveyance and treatment, which is a considerable additional cost (Tilley et al., 2014), might be needed to prevent exposure.

Anaerobic baffle reactors (ABR), which have a similar primary treatment function to septic tanks, also achieve limited pathogen removal. ABRs are commonly installed in decentralized wastewater treatment systems in LMICs. While the retention time is longer than for septic tanks, research in South Africa found approximately 1 log removal for bacteria, viruses, and protozoa, and about 2 log removal for helminths (Foxon, 2009). Further treatment is necessary to meet most national effluent standards (Tayler, 2018). Analysis of the performance of 50 small-scale sanitation systems in South Asia, including ABR-based systems and more advanced technologies, found that almost all systems consistently failed to meet microbial water quality standards, with no improvement in systems fitted with a disinfection step (EAWAG, 2018). Most of the systems in this analysis had effluent fecal coliform concentrations of 10^4 – 10^6 MPN/100 mL. In line with this, WHO (2018) guidelines state that the effluent and sludge from ABR and anaerobic filters have high pathogen levels and require further treatment. However, these systems often discharge directly to local drains or waterways. Constructed wetlands provide a simple additional pathogen reduction option, but they require additional land area (Tayler, 2018).

Off-site sewerage may avoid many of the above challenges, but it does not necessarily solve all contamination issues as leakage can occur during conveyance, and even with advanced treatment processes some wastewater effluent still contains high levels of pathogens (WHO, 2018). Leakage can happen due to: misconnections (where a sanitary or graywater sewer pipe

is connected to a surface drain unintentionally); structural deficiencies resulting in exfiltration into groundwater supplies; flooding events resulting in combined sewer overflows entering surface water; or sanitary system overflows whereby sewage flows into stormwater systems due to clogged or broken pipes, infiltration, or power failures, and results in discharge of untreated wastewater into surface water bodies (Williams and Overbo, 2015). Most national wastewater effluent standards do not include pathogen targets (WHO, 2018; Tayler, 2018), despite the continued exposure risk if the receiving waterway is used in agriculture or for recreation. Similarly, the target SDG 6.2 also considers secondary treatment to be safe (WHO, and UNICEF, 2017) despite the fact that pathogen reduction in accepted technologies is typically inadequate (WHO, 2006). Ultimately, decisions about the level of treatment must consider the downstream exposure risk, as proposed in the draft SDG definitions (WHO, 2016) or as suggested in sanitation safety planning (SSP) (WHO, 2015).

Container-based sanitation (CBS) is a recent development that may provide opportunities to prevent contamination of groundwater and surface water, particularly in dense low-income settlements. In general, these are mostly urine-separating toilets in which fecal matter is collected in a bag or container (replaced regularly by a local enterprise and taken away for further fecal sludge treatment) and diverted urine is typically disposed of in drains or sewers, or infiltrated into the soil (Mara, 2018; World Bank, 2019). In Cape Town, South Africa, a utility is operating a related low water-use system with a 20 L container collected twice weekly then emptied, cleaned and disinfected mechanically at the local sewage treatment plant (Willetts, 2019). Yet CBS and onsite systems requiring pits or tanks to be emptied all potentially create significant risks to sanitary workers, and this issue requires proactive management (Mackinnon et al., 2019; World Bank, 2019).

The risks to public health arising from inadequate sanitation are driven by both the extent of the hazard that enters the environment and the probability of human exposure to that hazard. In addition to understanding the source and ability of different 'technologies' to reduce contamination of the urban living environment, it is important to understand the *exposure* and how this varies across a city context, including related inequalities. Low-income households are at greater risk from exposure, as they are more likely to be in areas affected by sewage and septage overflow during floods (Hawkins et al., 2013). The identification of locally important key fecal transmission pathways, and an understanding of a person's full exposure to fecal pathogens, can provide valuable information for the prioritization of interventions (Robb et al., 2017; WHO, 2018; Wang et al., 2018). Various studies have found that exposure and health risks are associated not only with an individual's sanitation but also the sanitation of their communities (Hunter and Prüss-Ustün, 2016; Wolf et al., 2019). For example, in Timor-Leste, although only 7% of the urban population uses toilets that flush to an open drain, 55% live in communities where at least one household uses a toilet that flushes to an open drain, potentially exposing many households in the neighborhood to pathogens (UNICEF and WHO, 2019). Equally, not all fecal contamination

may be an exposure risk. For example, if shallow groundwater is not used due to alternative available, affordable and convenient drinking water options, then groundwater contamination may carry a lower risk. A citywide approach also calls for the exposure risk of all population groups to be addressed, including at-risk groups such as sanitation workers and farmers who are exposed to dumped sludge or untreated wastewater (Farling et al., 2019).

One of the major challenges in assessing contamination and health risk is the complexity of the science involved. Several efforts have been made in recent years to create simple assessment tools and approaches that can facilitate a general conversation about the relative scale of risks and the consequent investments that could be prioritized to reduce such risks. Since 2006, WHO has been focusing attention on the fact that the health impacts of sanitation and wastewater management are a product of both hazard and exposure. The 2006 Guidelines for the Safe Use of Wastewater, Excreta and Graywater (WHO, 2006) provide a framework for this analysis but have been widely reported to be complex and difficult to apply. SSP is a city-level tool based on this risk-assessment approach, which provides a more simplified framework that can be used to identify and assess health hazards and exposure pathways in a city (WHO, 2016). Where the application of SSP is challenging, an even simpler starting point is provided by the Shit Flow Diagram (SFD), a simple graphical representation and assessment of the fate of excreta in urban areas across the sanitation service chain (Peal et al., 2014). The SFD highlights the relative scale of flows from all relevant sanitation systems, and it identifies those which are broadly 'safely managed' and those which are broadly 'unsafe.' The SFD distinguishes between hazards that remain in the neighborhood and those that reach citywide drainage or are discharged downstream of treatment facilities. At a smaller scale, the Sanipath assessment tool provides much more detail on the relative importance of different exposure pathways in a neighborhood (Robb et al., 2017).

All these tools are based on risk assessment methodologies, and a further step is to draw on dose-response and infection-disease models. These are often brought together using quantitative microbial risk assessment (QMRA), which has been applied to determine the magnitude of risks to different population groups from contamination (Labite et al., 2010; Fuhrmann et al., 2017; WHO, 2019) and informed a conceptual approach developed to assess different sanitation options (Mills et al., 2018). The sanitation option generation model developed by Spuhler et al. (2018) includes public health as one of five criteria, although the assessment is limited to a scoring of technology compliance against effluent discharge standards. Further quantifiable methods for comparing and prioritizing sanitation improvements are needed that can address the risks caused by different failures along the service chain, to different user groups and at different scales.

The recent synthesis of sanitation and health-related research (Murphy, 2017; WHO, 2018) has highlighted several remaining knowledge gaps, particularly the absence of information relevant to conditions in LMICs. A key area for further research is the fate of pathogens in urban environments, particularly protozoa and helminths in sewers or drains (Murphy, 2017). Where

onsite systems are prevalent, key research gaps include: the partitioning of different pathogen types in sludge and effluent; the effects of efforts to improve the performance of existing systems (e.g., regular emptying); and the potential for further pathogen reduction through additional onsite or decentralized secondary treatment processes. While modeling pathogen flows and improvement options can begin to inform options and priorities, there is also a need to balance complex analysis with simple decision trees or rules of thumb that can be more easily applied by decision-makers to ensure the highest-priority areas are given attention. Context-specific risk-based thinking is key, as promoted by the SSP approach, since population density, soil type, environmental conditions, stormwater hydraulics, groundwater contamination vulnerability and exposure pathways will inevitably differ from place to place. Without this approach, there can be no sound basis for comparing sanitation options in terms of their potential to meet public health risk objectives.

CLIMATE CHANGE

Climate change is a critical issue of our time and stands to severely impact sanitation systems both directly and indirectly. One way it may do so is by exacerbating the risks of fecal contamination and disease spread discussed above. The gravity of the situation has only recently been recognized, and it is timely to consider how climate change could and should be incorporated into sanitation decision-making frameworks to improve resilience (World Bank, 2011; ISF-UTS and SNV, 2019; WHO, 2019). When adopting a citywide, inclusive perspective, the issue becomes even more relevant, since the worst impacts are likely to fall upon vulnerable and marginalized groups (OHCHR, 2010). Climate change demands that we ask how technologies and service arrangements at various scales could be expected to perform under different climate-related scenarios, such as increased flooding or drought, such that this can be considered in decision-making processes. Equally, it represents an imperative to consider the mitigation potential of different options when selecting optimal solutions.

If global warming continues at current rates, it is predicted that climate change will substantially increase the frequency and magnitude of extreme flooding and drought in many regions, cause sea-level rise that will critically impact infrastructure in low-lying coasts, and drive increased variability in precipitation (Pendergrass et al., 2017; Hoegh-Guldberg et al., 2018). While the magnitude and complexity of the threats posed by climate change are increasingly well understood and documented, relatively little attention has been given to how these threats will impact drinking water and sanitation services and their management, despite their importance to human health (Howard et al., 2016). In this section we highlight key impacts of climate change on sanitation and disease spread, and current predictions about the performance of different solutions. It provides insights that can help ensure climate resilience becomes an integral consideration in decision-making about sanitation.

The impacts of climate change on sanitation are expected to be at least as significant as those on water supply, and in some

circumstances, they may be even greater (Howard et al., 2016). The most frequently reported hazard to sanitation systems is high-intensity rainfall, causing flooding of onsite systems such as pit latrines and septic tanks, which poses serious public health risks (Braks and De Roda, 2013; Cann et al., 2013; Howard et al., 2016; Bornemann et al., 2019). Flooding of pit latrines, due to rising groundwater or the inundation of surface water, renders them inoperable and may readily disperse excreta into the groundwater or surface flood waters, creating a severe risk in areas where they are present in high numbers (UN-Habitat, 2008; Charles et al., 2009) or for low-lying or densely populated areas (UN Water, 2019). In the United States, England, and Wales, cryptosporidium outbreaks have been associated with flood events (Hunter, 2003) and a systematic review shows vibrio cholera as the most common pathogen implicated in extreme water-related weather events (Cann et al., 2013). While raising latrines is a commonly proposed adaptation solution, it needs to be considered in the context of the population that will be using the facilities, as some adaptations may cause the latrines to become inaccessible for the elderly, children and people with disabilities (Charles et al., 2009). Various studies have indicated an additional hazard from flooding of on-site systems when residents take advantage of floodwater to flush out their latrine contents (Chaggu et al., 2002, as cited in Charles et al., 2009; Williams and Overbo, 2015). In contrast, the effects of flooding on container-based systems (CBS) could be expected to be minimal because they do not leak into the environment (World Bank, 2019). However, CBS faces similar risks to onsite systems if access for emptying or treatment is affected.

High intensity rainfall also affects centralized sanitation systems, including potential damage to wastewater treatment plants (Howard et al., 2016), destruction or interruption of sewer mains and pump stations (Moyer, 2007) or sewer overflows (Major et al., 2011). In many cities, combined sewerage systems are used instead of separate sewers due to lower capital costs, particularly where the existing drainage network is used. However, in areas where there is expected to be an increasing risk of wet weather, the high risk of pathogen exposure from combined sewer overflows means they should be considered as an incremental control measure only, and must be combined with other measures to prevent exposure during or following rain events (e.g., public awareness of overflows and temporary closure of contaminated bathing sites) (WHO, 2018).

Drought and water scarcity have different impacts on each sanitation system type. In fact, it is the risk of drought and water scarcity that identifies centralized sewer systems, and to a lesser extent septic tanks, as the most vulnerable types of sanitation (Charles et al., 2009; Howard et al., 2010; Sherpa et al., 2014; Luh et al., 2017; Fleming et al., 2019). This is because drought and water scarcity can reduce the usability of water-based sanitation and cause sewers to block (Howard et al., 2010). During periods of water scarcity in a peri-urban community in Botswana, residents with toilets connected to a sewer reverted to using old pit latrines, or built new ones, putting water supplies further at risk due to contamination (McGill et al., 2019). Other studies have found composting toilets and pit latrines are the most resilient to climate change, as they do not rely on water supply

(Sherpa et al., 2014; Luh et al., 2017) or because adaptations are feasible (Howard et al., 2010). Septic tanks are considered more reliable than sewers, as the risk of clogging during water scarcity is lower due to the shorter pipe distance, with decentralized or solid-free sewers also found to be more resilient than centralized sewerage (Sherpa et al., 2014).

Whilst less commonly reported in the literature, sea level rise can have direct impacts on sanitation systems. Sea level rise and surges present a risk to the sewer outfalls that are common in coastal areas, as wastewater can back up and flood through manholes in roads and the toilets and washbasins of homes and buildings (PAHO, 1998; CEHI, 2003). Saltwater intrusion to sewers or wastewater treatment plants may also affect biological treatment processes (WHO, 2019).

More generally, climate change is expected to affect the fate and mobility of pathogens (Charles et al., 2009). As a result, climate change is likely to exacerbate existing health problems, including those related to poor sanitation (IPCC, 2014) and the spread of water-borne diseases (UN Water, 2019). Rising temperatures are also expected to increase the incidence of diarrheal disease (Hutton and Chase, 2016). Climate factors determine the number, type, virulence and infectivity of pathogens transmitted through water or vectors that breed in water, and thus they may impact the associated infectious diseases (Vo et al., 2014). Increased precipitation intensity will create peak concentrations of pathogens in waterways due to sewage overflow and runoff (Vo et al., 2014). Increased groundwater flows and levels due to more rainfall and frequent or larger floods promote the spread of pathogens through greater mobility and survival, and greater saturation of soil increases pathogen survival (Charles et al., 2009).

In efforts to satisfy environmental objectives for sanitation, mitigation is also an important consideration. Human excreta is a source of greenhouse gas (GHG) emissions, and pit latrines have been estimated to account for approximately 1% of anthropogenic methane emissions globally (Reid et al., 2014). Biological processes in wastewater treatment plants are also believed to be significant GHG contributors in some countries (Mannina et al., 2016) and septic tanks are considered to be major contributors (González et al., 2018; Somlai et al., 2019). Composting toilets and regular emptying of septic tanks are proposed to reduce GHG emissions (Reid et al., 2014, IPCC, 2006), as are options that limit energy use in sewage conveyance. Examples include gravity-based systems and decentralized systems that reduce pumping distances as compared with centralized solutions (Carrard and Willetts, 2017) and blended gray-green-blue¹ infrastructure (UN Water, 2019). Further research is needed to develop a more nuanced understanding of GHG emissions from different types of onsite systems under common usage across LMICs.

So what does this mean for decision-making and options assessment? Global comparative studies on the performance of each technology under varied climate change scenarios, and

evidence on emissions, need to be carefully applied in context-specific decision-making processes, taking into account the local climate, and technical and environmental factors. Risk-based approaches, as discussed above under 'Contamination,' remain applicable. However, they must be complemented by new thinking in relation to addressing uncertainty.

Climate change creates uncertainty due to our limited understanding of how climate hazards will change in specific locations, how climate change interacts with other forces (e.g., urbanization and land-use change), and how society will respond (Dessai and Hulme, 2004). In addition, the social systems connected to service use and management, and the interactions between social and bio-physical systems, need to be considered (Kohlitz et al., 2019). Often, technical and management systems for urban sanitation are poorly equipped to handle uncertainty and changing conditions. Addressing both dry and wet extremes calls for solutions at different scales ranging from the household level up to the city level (UN Water, 2019). A study on adaptability by Luh et al. (2017) found that no sanitation system performed well in all hazards, suggesting that the resilience of sanitation technologies is highly dependent on which climate-related hazards are considered. Despite uncertainties about the specific future impacts of climate change, cities can make informed decisions about how to increase resilience and adapt based on the best available information (Dessler and Parson, 2010). The field of climate adaptation commonly promotes nature-based systems and blended gray-green-blue infrastructure, which are suggested to be more cost effective, less vulnerable to climate change, offer mitigation co-benefits and provide better service and protection over its lifetime (UN Water, 2019). 'Low regrets' approaches to sanitation development – approaches that are beneficial regardless of the climate scenario – should also be pursued (Oates et al., 2014). Examples include: the scheduled emptying of latrines in advance of flood seasons, low water-use toilets and improved construction quality to reduce the infiltration of water into septic tanks or sewers.

Incorporating principles of adaptivity and flexibility into infrastructure and service arrangements is expected to assist managing sanitation systems in the context of uncertainty. Several water and sanitation professionals have argued that as an adaptation strategy, the diversification of facilities is preferable to focusing on just one type of facility or a centralized system, as a mix of facilities can increase resilience and diversify risk (Charles et al., 2009; ISF-UTS and SNV, 2019). Being able to change the management and operation of sanitation services and ensuring operators have a good understanding of sanitation system components increases the adaptability of services to changing conditions (WHO, 2019). Adaptive management improves responsiveness to different conditions by promoting continued learning through experimentation, feedback and innovation. Adaptive management measures could include preventative maintenance, involving operators in design and decision-making, and increased system monitoring connected to response or warning mechanisms (ISF-UTS and SNV, 2019).

In the context of supporting inclusive citywide sanitation decisions, attention must be given to vulnerable populations. Climate change does not affect everyone equally, and low-income

¹Gray infrastructure refers to entirely human-built 'hard' systems such as pipes, levies and concrete dams. Green and blue infrastructure includes natural elements such as a floodplains or coastal forest but can also be engineered by humans (UN Water, 2019).

households are more likely to be in areas affected by sewage and septage overflow during floods (Hawkins et al., 2013). Low-income households are also more likely to use precarious sanitation systems that are easily destroyed or disrupted by climate hazards, and they typically possess the least capacity to cope with and adapt to shocks (Grasham et al., 2019). Urban sanitation decisions must take account of the differential impacts of climate change across social groups and their capacity to respond to those impacts. Climate risk assessments, the mapping of areas exposed to climate-related hazards, and social vulnerability indexes can be used to measure the vulnerability of populations, and overlaid with maps of flood, water scarcity or landslide hazards to identify areas where sanitation services could be disrupted (WHO, 2019).

It is critical that resilience and mitigation efforts be mainstreamed into current decision-making, rather than seen as an additional concern, given the long-term implications of today's development decisions and the need to avoid even greater costs in the future (World Bank, 2011). Acknowledging the uncertainty of climate predictions, and recognizing that in many cities sanitation systems will be affected by varied climate impacts, options should be selected that minimize regret (Oates et al., 2014; Hallegatte et al., 2019). When bridging the gap between climate science and infrastructure planning, addressing the complexity and uncertainty of climate impacts could result in paralysis in planning. Bornemann et al. (2019) suggests the need for better communication and explicit training designed to provide the next generation of key decision makers with additional appropriate analytical and problem-solving skills. Stress testing options under a range of plausible climate conditions relevant to the local context may assist in the management of uncertainty, and may help decision-makers to debate trade-offs between robustness, cost, safety margins, flexibility and regret (Hallegatte et al., 2019). More broadly, considering climate adaptation and mitigation also means that planning and policies need to incorporate and address the interconnections between climate, water resources, sanitation and water infrastructure, rather than consider these issues separately (McGill et al., 2019).

COST

Achieving citywide inclusive sanitation requires investment in infrastructure that meets the needs of all urban areas, including low-income settlements. It is widely recognized that ensuring the provision of citywide sanitation services involves high capital and operational costs. Cities need to consider how to provide universal access to safe sanitation through suites of technologies and operating configurations that incur the lowest cost to society as a whole. This requires addressing long-term financial liabilities, rather than short-run investments or budgeting constraints, and it therefore requires an understanding of the full life-cycle costs and relevant externalities of different sanitation options (Mitchell et al., 2007). However, there is a paucity of data on the relative costs of different options for providing sanitation

services in urban areas, as analyses are generally confined to capital cost comparisons rather than life-cycle costs (Daudey, 2018). Consequently, there is a shortage of data to inform decision-making about possible service scenarios to achieve citywide sanitation.

While several recent studies have provided critical financial perspectives for urban sanitation, they have focused on discrete aspects of the issue. These include: studies of willingness to pay (for example, Vásquez and Alicea-Planas, 2018; Acey et al., 2019; Tidwell et al., 2019); the business case and cost recovery for fecal sludge management (e.g., Andersson et al., 2017; Blackett and Hawkins, 2017; Otoo and Drechsel, 2018); and analysis of the pro-poor reach of infrastructure investments (Hutchings et al., 2018). Analyses comparing sewer and onsite technologies exist (Dodane et al., 2012; McConville et al., 2019) but can be limited by inconsistent analytical boundaries due to the exclusion of costs borne by households (for example Stantec, 2019). These types of analyses do not address the fundamental need for cost comparisons and decisions across different scales, technologies and service options. Such comparisons are needed to broaden the suite of options considered beyond the dominant investment focus on large-scale wastewater treatment and sewerage systems (Hutchings et al., 2018) that typically serve better-off socio-economic groups (McGranahan, 2015). This section outlines the evidence base to date, and points to important areas which need to be included in the robust consideration of costs in citywide sanitation decision-making.

A recent review (Daudey, 2018) confirmed that available contextualized data on the costs of urban sanitation solutions is surprisingly limited and of variable quality. However, the body of literature does identify some typical cost characteristics for urban sanitation systems. In general, “lower tech” (typically onsite or simplified sewer) solutions are considered less costly than “higher tech” (conventional centralized) systems. However, the systems under consideration typically do not offer equivalent levels of service or treatment (Daudey, 2018; Rozenberg and Fay, 2019) and as such are not directly comparable. This is of concern given the above sections discussing contamination and public health risks, including the exacerbation of these with climate change. In addition, across the lifecycle of sanitation infrastructure, the expenditure required for operation and maintenance (compared with capital expenditure) is highly variable. Daudey (2018) found that operations and maintenance expenditure ranged from 6% to more than 60% of total expenditure, with a lower proportion in the case of centralized sewerage systems (given their high capital costs) and a higher share for FSM-based systems (Dodane et al., 2012; Daudey, 2018; Stantec, 2019). However, such comparisons are not useful for informing investment decisions, since they do not provide a basis of comparison between options with a consistent metric. In addition, the costs of sanitation systems are highly contextual, with determinants related to technical, topographic, demographic, socio-economic and material factors (Daudey, 2018). For example, when modeling the costs of onsite and offsite options for the delivery of sanitation in Soweto, South Africa, Manga et al. (2019) found that population density and rates of connection to sewers had a significant impact on the relative

costs of systems, with sewers becoming attractive from a cost point of view once population densities exceed a threshold value that varies depending on the extent of pumping and treatment options.

The challenges associated with defining typical cost characteristics of sanitation options are compounded by limitations in the available evidence. Daudey (2018) identified three main limitations in the literature on urban sanitation costs: inconsistent inclusion of life-cycle costs; failure to include costs for the whole service chain; and a lack of transparent reporting on the costing methodology. Few analyses transparently include life-cycle costs, with many focusing on only one or two cost types or neglecting to disclose which costs are included. Only six of the 50 studies reviewed in Daudey's (2018) analysis included at least capital, recurrent and capital maintenance costs. The review itself also excluded expenditure on direct and indirect support, two cost components identified in the WASHCost costing approach (Fonseca et al., 2011) that are critical for the sector to move toward professionalized management arrangements for service provision. Exploring the costs associated with direct and indirect support activities would be a valuable contribution from future cost analyses seeking to inform citywide inclusive sanitation. Analyzing these costs requires an assessment of the costs associated with economic and environmental regulation, inter-sectoral coordination, monitoring and IT systems (Fonseca et al., 2011). Full life-cycle costing in cost-effectiveness analyses must also acknowledge the different expected life spans of infrastructure alternatives in order to compare options on an equal footing. Such comparisons need to take into account anticipated phasing of investment and differences in asset capital and operating cost profiles over time (Mitchell et al., 2007).

The second limitation Daudey (2018) found in the literature was that many studies fail to include costs across the whole sanitation chain (containment, emptying and transfer, treatment, reuse/disposal), with fewer than half the reviewed studies (19 of 50) addressing at least containment, emptying and transfer. Studies which focus only on parts of the service chain risk misrepresenting the true costs of services, limiting their usefulness in investment decision-making for citywide services. Potential benefits or revenue streams can also be missed if the full chain is not included (Willets et al., 2010; Andersson et al., 2016; Lazurko, 2019; Trimmer et al., 2019). It is also necessary to consider the potential increased demand for some resources such as nutrients for fertilizers, with scarcity increasing chemical fertilizer prices and demand for alternatives such as treated sludge expected to increase, attracting investment (Hutton and Chase, 2016).

The third limitation identified by Daudey (2018) was that reporting of cost analyses was often opaque in terms of methodology and specification of the options considered. This limits the extent to which included data can be interpreted as relevant (or not) for planning in different contexts. This illustrates a sector-wide challenge that cost information is not commonly presented in a form suitable for informing decision-making (Hutton and Chase, 2016), and there is no widely accepted and agreed cost-effectiveness methodology. Another challenge for citywide service planning is that

the costs of ensuring inclusive services for the hardest-to-reach populations are not well understood and are easily underestimated (Hutton and Varughese, 2016).

A critical consideration for improving our evidence base is comparing system costs for options that meet an equivalent, specific objective (Mitchell et al., 2007). In the case of sanitation, the specific objective is to choose a service level that protects public health and the environment and addresses the contamination issues discussed in the section 2 of this paper. Clarifying this objective is necessary to prevent the inappropriate direct comparison of options with different service levels, such as comparing onsite systems without secondary treatment to sewer systems. To achieve a similar level of service, the costs of reducing the hazard or exposure associated with onsite systems (for example through secondary treatment) should be included in order to provide a more appropriate assessment of relative costs (Mitchell et al., 2016). Similarly, costing any system, whether it is an onsite, onsite or container-based system, without costing the relevant required management, for instance the costs of regular desludging or maintenance, is also misleading, since the required service level cannot be maintained without incurring these costs. To support defensible cost comparisons on a level playing field, options should be required to reach a minimum tolerable level of public health risk. This will require an approach to risk assessment that can inform costing analyses.

The costs of climate change adaptation measures to ensure a minimum ongoing service level and tolerable contamination risk should also be considered. Predictions are needed for expected performance in different climate scenarios, such that maintenance and repair costs for adaptation and response can be integrated into the cost analysis (World Bank, 2011). This is likely to be challenging, given the uncertainties associated with climate change, but also cannot be ignored. The various climate hazards associated with urban sanitation discussed above will increase maintenance costs, as repairs and replacement expenses are expected to become more significant and frequent. Floods are among the most costly types of disaster, especially as they increase in frequency and severity (Cissé, 2012 in Sherpa et al., 2014). The costs of adaptation measures should therefore also be considered. Examples of adaptation measures include increasing the resilience of infrastructure by providing additional flood protection for latrines or treatment plants, increasing the capacity of sewers, and sealing pit latrines. Equally, decisions about whether to prioritize more robust or easily rebuilt low-cost infrastructure must be made. For example, the Char communities in Bangladesh, who have a history of exposure to rainfall variability and adapting their lifestyle (e.g., through migration) build more temporary low-cost structures that can be rebuilt rather than expensive permanent structures that would regularly be abandoned (Charles et al., 2009).

Climate change will also increase operational costs, particularly for centralized sewerage systems. This is due to the increased cost of energy as well as the pumping and treatment costs associated with increased volumes of wastewater and stormwater due to precipitation increases (Major et al., 2011). In addition to the costs of repairing and replacing damaged infrastructure as sea levels rise, cities may no longer be

able to rely on gravity to discharge combined sewer overflow and wastewater effluent, and this will increase pumping costs (World Bank, 2018). Adaptive management can increase operational costs, for example due to increased human resources and training costs, asset management systems, and monitoring and warning systems. While these are necessary in non-climate change conditions, addressing the specifics of climate change adds another layer of complexity to evaluation and decision-making processes for city planning that is already challenged by incomplete information about the range of future costs (World Bank, 2011).

As a way forward to inform decision-making, cost-effectiveness comparisons should ensure system-wide, consistent boundaries of analysis such that different infrastructure configurations, considering the whole service chain, can be appropriately compared. This requires taking a whole-of-society perspective which considers all costs over time and identifies which options represent the least cost to society to achieve the specified service level (Mitchell et al., 2007; Willetts et al., 2010). Including all cost perspectives (e.g., user, operator, initial investor) is particularly critical when comparing options with substantially different cost profiles in terms of their distribution and timing (Mitchell et al., 2007).

Once a sanitation option is decided upon that incurs the least cost to society, decision-makers can then develop mechanisms for financing the selected option and determine an appropriate distribution of costs across different stakeholders to ensure affordability for low-income households (Mitchell et al., 2007). Transfer payments may be required, for example an appropriate household payment to a service provider, or a subsidy from a municipality to a service provider. This is critical when considering equity in citywide sanitation, particularly as low-income areas may require higher cost solutions due to their hard-to-reach locations or higher-cost-to-user solutions such as onsite systems. Decision-makers could also change the way costs are distributed, as households who pay for FSM-based onsite systems and emptying services typically incur a greater portion of costs than those with centralized systems for which a larger share of costs is borne by utilities and other service providers (Daudey, 2018; Dodane et al., 2012). With the complexity of the sanitation chain and its multiple actors and institutions, it remains a significant challenge to conduct robust costing analyses at the 'system' level. However, without this, there is potential for chosen service systems to burden governments and society with expensive solutions, or to inadvertently disadvantage the poorest and most vulnerable, for instance by only costing and examining one part of the sanitation chain in isolation.

IMPLICATIONS

While the interlinkages between contamination, climate change and costs for sanitation options and investment decisions were noted at the end of each section, there are three key cross-cutting challenges which are important to draw out.

Firstly, the burden of contamination, climate change and costs associated with sanitation is unequal. To date, reducing

inequalities has mostly focused on access to services. However, inequalities in exposure to fecal contamination, particularly in the face of climate change (notably flooding) also warrant attention and are under consideration in the evolution of monitoring of SDG 6.2. The cost burden of living with elevated risk of contamination and climate change effects such as flooding falls disproportionately on the poor. To date there has been limited work on how costs of building resilience should be equitably shared.

Second, inadequate data and evidence gaps limit informed decision making across each of these three areas. Research on the fate of different types of pathogens in dense urban living environments is urgently needed to address contamination (Amin et al., 2020; Foster et al., 2020). For climate change we require cohesive ways to bring together disparate climate science, engineering, public health and social science knowledge. As noted earlier, accumulation and analysis of cost data across different sanitation options for the full sanitation service chain is only recently emerging.

Third, whilst this paper primarily tackles the technical inputs needed for improved decision making, in reality we recognize the significant role of politics and power dynamics in real-life decision-making. That is, sanitation investment decisions rarely follow a rational planning process, as there are many additional factors that intervene, such as politics, ideologies, implicit beliefs and assumptions, restrictive policies or standards, and insufficient confidence to deviate from traditional approaches (Abeyuriya et al., 2019). The top-down influence from politicians, funding agencies or other investors may also shift focus to capital and/or large investments rather than the ongoing expenses or consideration of progressive improvements that are important for sustainability.

This said, a risk-based approach to decision making will remain important to identify and target interventions which address inequalities; such an approach is vital to ensure that incremental investments are selected based on their comparative cost effectiveness in terms of their broader benefit to society. A stronger understanding of pathogen flows and climate hazards is essential to enable decision makers to determine the highest priority risks and the real costs of their mitigation. Attention to these risks can also inform appropriate sequencing and prioritization of investment, and the effective delivery of incremental improvements. An incremental approach promotes a gradual build-up of capacity and allows feedback and incorporation of new information, which is particularly important in the context of climate change and rapid city level development. A key ingredient is therefore increased monitoring to understand the operation of sanitation systems, including from a financial perspective, as well as real time data to identify and manage risks. Critical for sustainability across all areas is an increased priority on operation and maintenance, without which the benefit of any investment will be effectively lost with consequent further downward pressures on both equity and resilience in the city.

Putting these approaches and research into practice requires new capacities to be built. Optimizing urban sanitation

investment decisions is a complex challenge, and it requires high levels of expertise and technical know-how at the city level. The skills required go well beyond the ‘technical’ engineering focus that has tended to dominate historically. Many of these skills may exist but are rarely brought together to facilitate a multi-dimensional planning process that balances positive health outcomes, sustainable services and cost effectiveness.

CONCLUSION

Contamination, climate change and costs are three aspects of sanitation that require critical attention in decision-making to ensure that sanitation solutions are chosen that achieve the public health, sustainability and economic objectives integral to inclusive citywide sanitation. Bringing a contamination and climate adaptation and mitigation focus to decision-making requires risk-based thinking and will emphasize the importance of addressing inequalities and prioritizing vulnerable communities, not just for equity but for citywide public health. Operation and maintenance are cross cutting challenges that must be considered upfront when investigating sanitation options, particularly how these options are to be resourced and financed. Analysis of cost effectiveness against consistent

service objectives will permit improved comparison of the mix of sanitation options likely to be appropriate to different contexts across a city. This will create an opportunity to then separately consider how costs may be fairly distributed across different actors. Research and data gaps need to be addressed, particularly in relation to fecal contamination risks and climate change, and particularly as relevant for the conditions found in dense low-income areas. With the large investment needed to achieve citywide sanitation for all, consideration of the three areas of cost, climate and contamination can enhance recognition of sanitation’s importance for a sustainable healthy city and important contribution to health, sustainability and economic outcomes.

AUTHOR CONTRIBUTIONS

JW, NC, JK, and FM conceived the objective of the manuscript and conducted background research. FM and JW refined framing and structure. FM took the lead in drafting the manuscript with contributions by JW (all sections), BE (contamination, abstract, introduction, and conclusion), NC (costing), and JK (climate). FM addressed reviewers’ comments. All authors reviewed the final version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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