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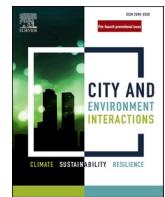
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Can sewerage be considered safe management of human feces?



Paul Minier ^a, Fabien Esculier ^{a,b}, Bruno Tassin ^a, Konstantinos Chatzis ^c

^a LEESU, Ecole des Ponts, Univ Paris Est Creteil, Marne-la-Vallée, France

^b UMR 7619 METIS, CNRS, EPHE, Sorbonne Université, 75252 Paris, France

^c LATTS, Université Gustave Eiffel, Champs-sur-Marne, France

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ABSTRACT

Although flush toilets and sewerage are usually considered the height of comfort in 21st-century urban societies and the technical and sanitary culmination of human excreta management, they are increasingly being challenged for their environmental footprint and financial cost. Alternative management methods, broadly termed “source separation”, are being developed to address these issues. However, the widely shared belief in the absolute superiority of sewerage for public health is hindering the development of such systems. In this paper, we briefly re-examine the contribution to public health of sewerage as a means of managing human feces, in both its historical development and current implementation. We suggest that management of feces by sewerage is just one element among others in a systemic change, that it usually occurred much later than the others, and that the epidemiological transition usually attributed to sewerage only was, as a matter of fact, strongly supported by associated improvements in drinking water, health care, hygiene practices and good nutrition. We show that risk control in seweraged cities is not based on a barrier between human feces and the environment (what we might call sanitation), but on barriers between a contaminated environment and the different uses of water. We call for a more comprehensive analysis of the effects of sewerage on public health, in present times and historically, not only at the scale of a city but at the broader scale of all impacted communities. We also call for a comparison of these effects with those of other sanitation systems that have much lower environmental footprint.

Introduction

Despite all the improvements in wastewater disposal over the past century in western societies, sewerage still has many environmental consequences: high consumption of water and of material and financial resources, pollution of aquatic environments, contamination of sewage sludge with micropollutants [50] and greenhouse gas emissions (especially N₂O in wastewater treatment plants) [40], etc. In addition, only a small proportion of the nutrients contained in wastewater return to the soil (5% for nitrogen in the Paris region) [13], while the synthetic fertilizers that are widely used in agriculture are manufactured from fossil resources and have a considerable environmental impact.

Source separation could limit pollution of the different environmental compartments (air, soil, water) and enable use of the resources contained in human excreta (nutrients, energy) [53,20,35,6]. Yet, source separation faces a strong socio-technical and cultural lock-in in western countries that are already equipped with sewers: path dependencies (existing infrastructures), no connection between agriculture and sanitation, lack of skills, lack of political support, etc. [24]. In these countries, source separation of urine has been developing

substantially for several years, especially in Europe [30]. In comparison, selective collection of feces is confronted to a specific obstacle: the often mentioned risk of transmission of potentially pathogenic organisms (PPO) [28,44]. This is mainly due to the widely accepted view that sewer systems are as a safe way of managing human feces [55].

Feces do pose a microbiological risk and mismanagement can cause enteric infectious diseases (EIDs) which are transmitted by the fecal-oral route. In countries with widespread sewerage, mortality rates associated with EIDs are low today (on average 2.5 deaths per 100,000 population in OECD countries) [56]. Before the widespread introduction of sewerage, this mortality was much higher, driven by epidemics of cholera and typhoid [34] and the development of source separation systems in urban areas comes up against fears of a resurgence in the morbidity and mortality associated with these EIDs.

The objective of this article is to open up a debate on the alleged health effect of sewerage management of human feces. For this purpose, we analyze the specific contribution of sewerage to public health, historically at the time of its development in industrial cities, and currently in countries that are poorly equipped with sewers. We also study potential exposure to PPO along the sewage management chain.

E-mail addresses: paul.minier@enpc.fr (P. Minier), fabien.esculier@enpc.fr (F. Esculier), bruno.tassin@enpc.fr (B. Tassin), kostas.chatzis@enpc.fr (K. Chatzis).

Sewerage is not the only intervention to have a health effect

At the beginning of the 19th century, almost no city in Europe managed disposal of human excreta through sewers. In Paris, a city with a well-documented history of human excreta management, the few sewers that did exist were mainly for rainwater collection. The principle for managing human feces was to collect them in cesspools located underneath houses (Fig. 1). Once filled, these pits were emptied and the material was spread on the fields [4,14,1].

In the early 19th century, mortality from EIDs was high in industrial cities, especially when cholera and typhoid epidemics broke out [34]. By the second half of the 19th century, most industrial cities were introducing household water [36,12]. This led to the adoption of the cistern flush toilet, which was more convenient for removing feces from households. The release of large amounts of water into cesspools that had been designed for much smaller volumes disrupted the system however, and caused serious overflow and disposal problems [49,22]. Widespread use of the cistern flush toilet greatly increased the nuisance and health risk [32,37]. Partly to solve the inadequacy of cesspools for cistern flush toilets, feces carried by flush were gradually allowed to be discharged into the sewer system, together with other household wastewater and rainwater. This wastewater was then usually discharged directly into the receiving aquatic environment. It was during this period, between the middle of the 19th century and the middle of the 20th century, that industrial cities underwent an epidemiological transition, marked by a decrease in EID mortality [34]. It is generally accepted that the switch of these cities to sewage systems contributed significantly to this¹ [16].

However, historical studies measuring the health effects of sanitation have yielded mixed results [33]. In fact, it is difficult, if not impossible, to assess the specific effects of sewage disposal on public health, as several factors were involved at the same time. First, the transport of feces through flushing and sewage systems requires a reliable water supply. In addition, drinking water treatment has been introduced over the same period [2]. It appears that, despite popular opinion in the health professions, the benefits of managing human excreta via flush toilets and sewage systems have not been clearly demonstrated, at least in terms of human health [16,33]. To assess the specific effects of sewage disposal on public health, it would be interesting to study cities that implanted sewerage long after establishing drinking water supply, such as Copenhagen [48] or Lyon [42].

Currently, EIDs still remain a major problem, causing an estimated 1.75 million deaths worldwide in 2019. They are the second cause of death in children under five years of age (525,000 deaths each year) [56]. Large disparities exist between countries due to differences in access to safe water, sanitation resources, hygiene practices, health care [10] or good nutrition which have shown beneficial effects on public health [9,15,17,57]. Unfortunately, most reviews do not distinguish the specific effects of sanitation from other interventions (safe water, hygiene education, etc.). Studies that have focused on sewage-based fecal management have shown a positive health effect from implementing this technique. A longitudinal cohort study in Salvador, Brazil, showed that an increase in sewer coverage resulted in a 22% reduction in diarrhea prevalence among children under 3 years of age [5]. Norman et al. [38] conducted a meta-analysis of the effects of sewers on diarrhea and enteric infections. They found that the impact of sewerage development was a 30% reduction in diarrhea prevalence.

Based on the results of these studies, we could assume that the effects of sewerage on public health may have been the same historically. Kesztenbaum and Rosenthal [25] studied the case of Paris and showed that sewage disposal through sewers led to an increase in life expectancy

of several years. However, as detailed in the contemporary studies, the beneficial effects of sewerage implementation depend on the quality level of the previous system and its management. Norman et al. [38] noted that where on-site sanitation works well, a smaller effect of sewerage on health can be expected. And indeed, from two studies on the effect of latrine implementation on health, Fewtrell et al. [17] estimated a 32% reduction in diarrhea, which is similar to the results from the two studies above. By transporting feces in a manner that keeps them away from human contact and outside of densely populated areas, sewers have a beneficial effect on public health. But unlike latrine systems in which feces are managed on site, sewerage sanitation shifts the danger to downstream populations.

From an urban to a regional scale of analysis

By eliminating the fecal risk from densely populated urban areas, managing human excreta through sewers may limit intra-urban contamination, but it shifts that fecal risk to downstream waters. At the urban scale, healthy conditions are ensured in cities by the distances between the point where water is taken for drinking, upstream from the cities, and the discharge of wastewater downstream from them. On a larger scale, by discharging contaminated wastewater, a city shifts the health and sanitation costs of disposal onto the communities located downstream. In very specific configurations where there is no human contact with the receiving area, this transfer may be considered safe. However, in the vast majority of situations, there are many and varied human activities in the areas to which the pathogens are transported. The risk is simply transferred to others.

Historical studies have shown negative effects of sewers on public health, particularly due to the contamination of drinking water by sewage discharges. In Metcalf and Eddy [37], the authors compiled cases of typhoid epidemics, primarily in the United States, that were investigated and found to be caused by sewage contamination of water supplies. Davenport et al. [11] hypothesized that the relative absence of cholera in some cities may be related to the late development of sewage systems. Contamination of drinking water is more significant, however, when the city discharges its wastewater into a lake. In the 19th century, Chicago's main water source was Lake Michigan, into which the city also discharged its sewage. The history of Chicago's water supply is primarily that of the city's efforts to prevent this pollution from entering the city's water system (remote water intake, permanent closure of all sewage outlets into the lake, water chlorination) (Ferrie and Troesken, 2008). Tarr [49] wrote: "Ironically, many of the cities that suffered most severely from sewage polluted water had themselves spent millions of dollars on sewerage systems to improve local conditions." Therefore, treatment of drinking water is mandatory and, together with sewerage, it forms a system to protect the population of the territory from EIDs.

In countries widely equipped with sewerage, few studies have focused on its effects on public health. In these countries, it is estimated that 75% of human illnesses due to swimming are attributable to viruses of human origin from discharge of wastewater [43] and in the case of the December 2019 gastroenteritis outbreak in France, the shellfish that caused it were contaminated with the same viruses [18]. Studies in countries with poor sewerage systems only consider the population for which the sewerage is installed and do not address the effect on populations located downstream from the discharge. To study the effect of sewerage on health, studies need to analyze the entire "sanitation chain", from the user interface and excreta and wastewater collection methods, to reuse or disposal of the product of the sanitation system and the other population groups impacted by contaminated environmental compartments.

Even in optimal operation, sewerage poses health risks

Management of human feces through the sewer is considered to be safe if the sewer carries the wastewater to a treatment plant providing

¹ BMJ (British Medical Journal) readers choose the "sanitary revolution" (introduction of clean water and sewage disposal) as greatest medical advance since 1840.

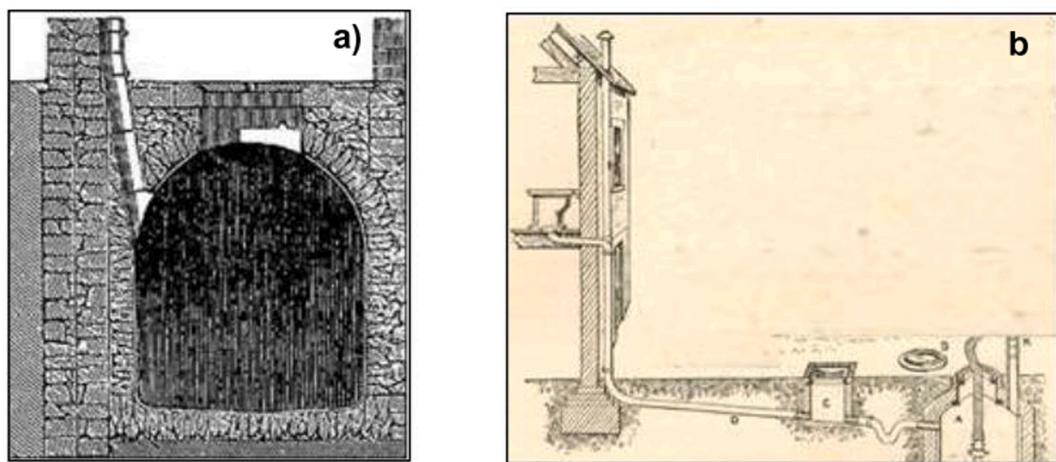


Fig. 1. Example of a cesspool without ventilation (XVIIIe s.) (a) and with ventilation (XIXe s.) (b) [1].

secondary or more advanced treatment [55]. However, sewerage can also have a negative effect on biological health risks. It has been shown that flushing leads to a release of aerosols that can be contaminated and remain in suspension in the bathroom. Using continuous and pulsed lasers to create a thin sheet of light, Crimaldi et al. [8] were able to illuminate the aerosols formed on flushing. These pose a risk of transmission of EIDs in heavily used facilities, such as public toilets [3]. Risks associated with sewers are multiple, meanwhile. If sewers are poorly connected or damaged, they can leak, causing wastewater infiltration into the ground and contaminating groundwater. During rain events, if the sewer carries both wastewater and stormwater (combined sewer system), the high inflow of rainwater can cause an overload of the sewer. This may cause overflows onto roads and backflows into homes, and also direct discharge into the river. Such direct discharge can also be a result

of connection failures in the sewerage system. Wastewater treatment plants (WWTPs) in general, are sources of bioaerosol emissions [19]. These pose a health risk to workers and people living around the plants [27]. Sewage sludge is also contaminated with various enteric pathogens from humans and animals. Prior to treatment, the sludge poses a risk to workers and must be managed to avoid exposure, including the possible transfer of pathogens to groundwater [21]. In most cases, WWTPs do not disinfect wastewater prior to discharge, except sometimes in specific contexts (e.g., to protect bathing sites). It is estimated that the reduction of pathogens between raw and treated water is about 2 log units for activated sludge WWTPs without disinfectant treatment. Secondary wastewater treatment reduces the concentration of pathogens, but is far from eliminating them completely. Fig. 2 summarizes the transmission pathways of enteric biological agents through the

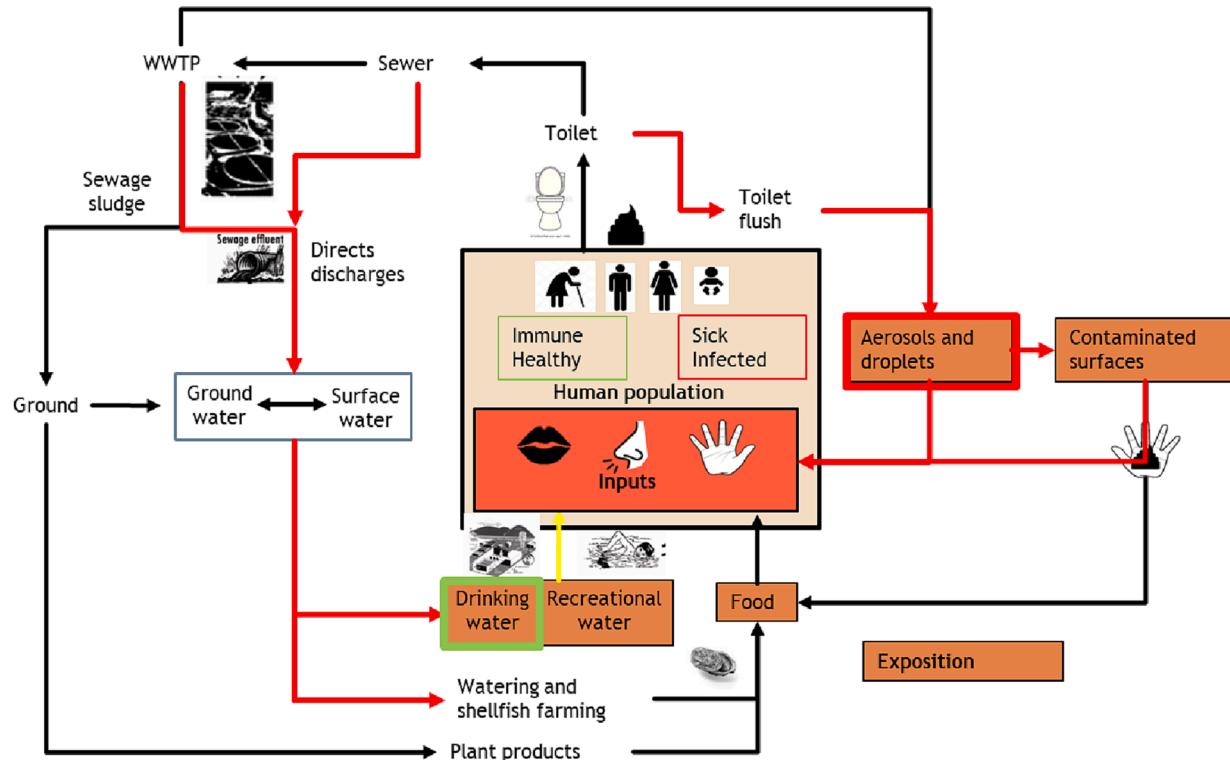


Fig. 2. Exposure pathways to enteric pathogens in the management of feces through flush toilet, sewer and WWTP. From red to yellow, the transmission risk gradient, with red inducing a high risk of transmission and yellow a low risk. Black arrows are undefined. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

management of human feces via the sewer. No cases of EIDs due to inhalation of enteric pathogens in aerosols produced by flushing toilets have been reported, but randomized studies are needed to demonstrate the existence, or not, of this pathway. Nevertheless, contamination of toilet cubicle surfaces poses a risk to users. The discharge of contaminated water into surface waters presents a risk for the users of this resource located downstream. One of the main risks is the use of surface water or groundwater as drinking water, for food production or for recreational purposes. As per the WHO definition, sewage is considered a “safely managed sanitation system” if the sewer carries wastewater to a treatment plant providing secondary or more advanced treatment. This definition seems valid to us only if the wastewater actually arrives at the WWTP and that the treatment makes it possible to disinfect the wastewater, and therefore to produce a barrier between the enteric pathogens and the environment, mainly surface water.

When the system is functioning properly, sewerage still poses health risks for populations, but these risks become much worse when the system fails. As explained in the previous reviews [5,38], many homes have water closets without a connection to a sewer, and wastewater is evacuated via an open drain. Dilution of fecal matter by flushing and its management through open drains increases the health risk on site, through groundwater contamination and direct contact of the population with the wastewater. In cases where toilets are connected to a sewer, meanwhile, the wastewater is not always treated. Although high-income countries collect and treat the majority of their wastewater (82% and 74%, respectively), the rates are very low in low-income countries (9% and 4%, respectively) [23]. When wastewater is not treated, it is released directly into the environment, exacerbating the problem of surface water contamination. Even when there are wastewater treatment plants, case studies observe malfunctioning of the plants for various reasons such as lack of electricity, poor maintenance, and under- or over-capacity of treatment [54,52,46]. Sewage sludge is also a health hazard and its mismanagement can present a risk to the population [45].

By the end of the 19th century, the biological health risks of wastewater discharge were known: drinking water, swimming, shellfish farming [37]. To prevent these risks, sanitary engineers recommended disinfecting wastewater. This technology is expensive, however, and is not considered enough by many engineers because of the direct discharge of wastewater in rainy weather via storm drains. It was therefore considered more efficient to not treat wastewater at all and to treat drinking water directly ([37], volume 1, p30). As the management of fecal matter through the sewer does not eliminate the fecal risk but shifts it to surface water, at a regional scale, the treatment of this same water for drinking purposes becomes crucial to protect public health. Advances in knowledge of drinking water treatment technologies (filtration, chlorination, UV) have made it possible to separate contaminated water by a barrier, forming a system to protect against EIDs in combination with sewerage. For bathing and shellfish farming, there are severe restrictions and areas are defined for these uses, far from wastewater discharge points, in order to prevent the risks of contamination.

Currently, the health problems due to sewage management of human feces are identical to those of the early 20th century: bathing, shellfish farming, drinking, etc. Kolsky et al. [26] studied fecal risk reduction for several fecal management technologies in Ghana, Indonesia, Mozambique, and Senegal. Of the technologies studied, wastewater treatment showed the worst results, due to the lack of a functional treatment for pathogen removal. Nevertheless, in a country such as France where water bodies show widespread contamination by fecal pathogens due to the sewerage paradigm, regulations have been introduced on the use of contaminated water: extensive treatment of water to make it drinkable, prohibition of bathing in certain areas (Directive 76/160/EEC), frequent prohibition of consumption of shellfish, etc. Risk control is therefore not based on building a barrier between human feces and the environment (what we might call sanitation), but on maintaining a barrier between a contaminated environment and the different

uses, such as drinking water. Sewerage, drinking water treatment and strict water use restrictions work as a system that can be considered a relatively safe way to deal with fecal matter. In cases where no such regulations and technologies are applied, sewerage poses a major public health risk. One in four people worldwide do not have access to drinking water free of microbiological contamination [58] and many households receive water through distribution systems that provide an intermittent water supply, in which pipes are regularly unpressurized, leading to post-treatment contamination [29]. In these settings, at a regional level, management of feces through sewers represents a severe risk for public health.

As the Sustainable Sanitation Alliance (SuSanA) points out, sanitation systems must respect certain criteria to protect human health: be economically and socially acceptable, technically and institutionally appropriate, protect the environment and natural resources, and function properly over the long term [47]. In essence, our analysis shows that the principal effect of sewage systems on infectious health risk is to displace enteric pathogens, shifting the hazard from one location to another. The resulting risk depends on the nature of the environments receiving the pathogens and the uses of these environments by downstream populations. In our research, we argue that a system used to manage human waste can be classified as “safe” as long as it prevents the transmission of enteric pathogens to other human beings. We can consider two possible options for the future of the management of human excreta in countries already largely equipped with sewerage. The first is end-of-pipe oriented, in continuation of the approach adopted heretofore. Improving the weak points in the existing system with end-of-pipe technological developments will certainly lead to an increase in the environmental footprint and financial burden of human excreta management, posing high risks of unsustainability [31]. Acknowledging that one century of development of sewerage to manage human excreta has still not led to truly effective sanitation, i.e., a barrier between human feces and the environment, the second option consists in developing source separation of human excreta in a paradigm that would be safe by design [44]. In countries that are poorly equipped with sewerage, engineers are starting to consider on-site technologies not only as long-term viable options, but possibly as a more sustainable alternative in many ways, compared to sewer-based systems. Onsite technologies can represent viable and more affordable options, but only if the entire service chain, including collection, transport, treatment and safe end uses or disposal, is managed adequately [45]. Very little research has been conducted in this field in countries already equipped with sewerage. We call for much broader work to understand the health risks associated with these sanitation systems and the solutions to prevent them.

Conclusion

The purpose of this paper was to question the assumption that management of human feces by flush toilets and sewers is effective and reliable, both in its historical and current forms. Our results indicate that the specific historical contribution of sewage systems to the reduction of EIDs is lacking in evidence, particularly because of the concomitance with other factors such as household water supply, drinking water treatment, health care, hygiene practices, and good nutrition etc. Conversely, these systems have had negative effects, particularly in cities where drinking water treatment was introduced late. Analysis of the biological health risks of sewerage shows that this management leads to contamination of the environment. This represents a risk for downstream users of the same water, which can be prevented with the implementation of drinking water treatment plants. Sewage and drinking water treatment work as a system that can be considered a safe way of dealing with fecal matter, as long as all other uses of contaminated water are strictly regulated (irrigation, bathing, shellfish farming, etc.). Without water treatment, sewerage may prove particularly harmful for downstream populations. Unfortunately, few studies currently focus on

these consequences. At a time of immense global change, humanity must now face up to new challenges (bacterial resistance genes, emerging diseases, etc.) in a difficult context (energy de-escalation, droughts, pressures on water usage, systemic risks that could jeopardize the stability of societies) [51]. In order for sewerage to be fit for purpose, significant curative technological investments will be required. This path does not appear to be compatible with the principles of energy and resource saving and preventive action. Other sanitation system paths need to be explored, particularly those involving source separation. We should further investigate these alternatives to sewerage and their deployment to reduce, and potentially improve, public health and effective sanitation for everybody.

CRediT authorship contribution statement

Paul Minier: Writing – original draft, Investigation. **Fabien Esculier:** Conceptualization, Writing – review & editing. **Bruno Tassin:** Conceptualization, Writing – review & editing. **Konstantinos Chatzis:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Minier reports financial support was provided by National College of Civil Engineering. Minier reports a relationship with National College of Civil Engineering that includes: employment.

Data availability

Data will be made available on request.

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