Novel integrated systems for controlling and prevention of mosquito-borne diseases caused by poor sanitation and improper water management

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A B S T R A C T

Mosquito-borne diseases, as a threat to public health, are primarily caused by the lack of clean water access and poor sanitation. On the way to overcome these problems, the sixth goal of Sustainable Development Goals (SDG–6) is imperative to improve sanitation practices and access to clean water supplies in a safe and sustainable way. By considering weak points of current centralized water and sanitation systems on the way to achieve SDG–6, finding sustainable approaches as alternative to unrealistic, unreliable and uneconomical water supplies (e.g. dams, groundwater and bottled water) and dangerous sanitation practices such as open defecation is essential to protect the public’s health against the recently spreading diseases such as Zika, Ebola, Malaria, etc. In this case, we developed novel integrated systems in which rainwater harvesting systems and waterless toilets, along with self-cleaning ponds. In this paper, suitable key elements and their roles in new water and sanitation management are introduced together with assessments of each key system identified for both public and residential zones. Comparisons with the current treatment plants by using economic analysis are discussed with reasonable parameters.

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1. Introduction

According to the United Nations and UNICEF, 2.5 billion people—more than 35% of the world’s population—suffer from poor sanitation that is spreading serious infectious diseases, such as Guinea Worm Disease, Trachoma, Ebola, and Malaria [1]. Recently, the Centers for Disease Control (CDC) has reported on the rapidly spreading Zika virus, especially in the American Tropics [2]. For example, there is evidence in Brazil that the Zika fever in pregnant women is associated with their fetuses’ abnormal brain development caused by the mother-to-child transmission of the virus, which may result in miscarriages or microcephaly [3].

Many developing and underdeveloped countries have failed to manage such water-borne diseases because centralized water and wastewater systems are not widely available, and existing systems in developing countries are poorly managed [4]. In order to manage mosquito-borne diseases, they are considering reapplying pesticides (mainly DDT) [3]. Such approaches are neither sustainable nor suitable for the environment. Instead, integrated water management strategies for accessing hygienic and safe water and sanitation can make the conditions unfavorable for mosquitoes to reproduce. The most sustainable and indispensable way for resolving these sanitation issues is by investigating the primary causes and then implementing preventive approaches. Therefore, new water and sanitation methods should be introduced.

This article aims to describe the weak points of the current water and sanitation practices that are increasing the potential for mosquito-borne disease breakouts and to present a novel independent and resource recycle-oriented water and sanitation system with that does not access any water infrastructure in order to provide safe and hygienic water as well as control the mosquitoes’ reproduction more efficiently in comparison with the current water and sanitation practices. In this article, three key invented technologies—a rainwater harvesting system,
an eco-toilet, and a Waterless Portable Private Toilet (WPPT) that can be integrated into two primary systems: one for public buildings and the other for residential houses. Construction and maintenance costs of these newly developed methods are compared with the currently used ones.

2. Challenges of current water and sanitation practices

2.1. Assumptions

To simplify the current water and sanitation problems regarding the spreading of mosquito-borne diseases, the situations for public zones and individual houses have been studied separately. Table 1 presents the assumptions used for the cost analysis of water and sanitation options in public zones and individual houses.

2.2. Problems in public zones

Existing methods for providing a clean water supply are from either surface water such as dam and lakes or a desalination plant that provides water from a far-away resource with high costs for treatment and facilities. This method may not provide enough water for a highly populated zone. As another water source, bottled water could be used, but this method is not cost-effective because a 20-L bottle may cost 1–2 USD and this totals more than 5000–10,000 USD per person per year. Another common option is utilizing groundwater, but this source is limited and the water quality is not reliable in most regions, thus adding increased costs for treatment units.

As for sanitation, the existing methods include open defecation in places that are not private or healthy and raise the risk of mosquito-borne disease breakouts. Indoor toilets are no better as they collect black water in a septic tank. These methods are not economical and may also cause odors. Treating the collected sanitary sludge is difficult and costly and causes contamination and makes the situation favorable for mosquitoes’ reproduction. Another option is to send the human waste to wastewater treatment plant via costly sewer piping system, but high loads of contaminants (e.g., nutrients, pharmaceuticals, personal care products, and micropollutants) sent to the wastewater plants cannot be treated properly and will eventually be sent to natural water sources, such as rivers or groundwater, thus causing pollution that potentially leads to the spreading of the mosquito-borne diseases [5].

2.3. Problems in residential community zones

Current water supplies from dams and lakes, desalination plants, bottled water, or groundwater have issues as mentioned in the case of public zones. In some areas, rainwater harvesting is an option, but if it is not managed well, the quality of the water will not be sustainable or reliable because of the high potential for oviposition of mosquitoes. As for sanitation, open defecation is very common and contributes to the problems previously mentioned. Drinking water demand in residential houses is much less than in public zones, and therefore, for residential areas, a smaller rainwater harvesting system could be utilized.

3. Introducing an integrated water and sanitation system

3.1. Key elements

3.1.1. Eco-Toilet

A novel resource-cycling toilet was developed that separates and stores feces and urine to compost them [5]. This toilet consists

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Table 1
Parameters Used for Example Cases of Water and Sanitation Options in Public Zones and Individual Houses.

<table>
<thead>
<tr>
<th>Public Building</th>
<th>Individual Houses</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Roof area: 460–500 m²</td>
<td>• Roof area (each house): 150 m²</td>
</tr>
<tr>
<td>• 300 people</td>
<td>• Ten households</td>
</tr>
<tr>
<td>• Drinking water consumption: 1L/capita/day</td>
<td>• Five people per house</td>
</tr>
<tr>
<td>• Annual water consumption: 100 m³</td>
<td>• Lack of access to a water supply</td>
</tr>
<tr>
<td>• Water: dams and other water supplies, bottled water, groundwater</td>
<td>• Water: dams and other water supplies, bottled water, groundwater, poor rainwater harvesting</td>
</tr>
<tr>
<td>• Sanitation: open defecation, septic tanks, wastewater pipes, and treatments</td>
<td>• Sanitation: open defecation</td>
</tr>
</tbody>
</table>

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Fig. 1. Schematic of Integrated Rainwater Harvesting System and Eco-Toilet for Public Zones.
of a bowl, a conveyor that disposes of waste at the lower side of the bowl, and a liquid fertilizer tank that converts the urine transferred by the conveyor. The toilet also has a conveyor cleaning apparatus for injecting the liquid fertilizer made from urine toward a moving unit that includes the bowl or the conveyor. Accordingly, feces and urine can be efficiently separated and recycled as compost and liquid fertilizer. One or more partition walls are installed in the liquid fertilizer tank so that urine overflows these walls, thereby increasing the efficiency of making the liquid fertilizer. In the liquid fertilizer tank, a predetermined amount of urine (one liter) and the

Fig. 2. Schematic of Integrated Rainwater Harvesting System [8] and Waterless Portable Private Toilet (WPPT) for Individual Housing [5,7].

Fig. 3. Solutions for Challenges in Public Zone.
urine seed agent ($6 \times 10^5$ cells per liter) as measured by the urine measurement sensor to the liquid fertilizer tank inoculum were optimized [6]. Both tanks are covered in order to limit access by mosquitoes.

3.1.2. Waterless portable private toilet (WPPT)

The Waterless Portable Private Toilet (WPPT) with a human waste separation device was designed as part of an integrated system [5,7]. This toilet is shaped like a box and can be folded for easy transport and assembly. The body includes a slanted plane that hides the feces. The toilet also includes a region separation bar over which a human waste bag is hung so that feces and urine can be stored separately. This portable toilet includes a coagulant in the urine storage region of the bag so that the bag can be reused several times. This system was examined during the Gorkha Earthquake on April 2015 in Nepal as a humanitarian service. The results show that the system can reduce the potential of transmitting viruses during outbreaks [7].

3.1.3. Rainwater harvesting system

This novel portable rainwater harvesting system was built with a storage tank and a transportation system [8]. There is also a smaller all-in-one, plug-and-play type of rainwater harvesting facility known as the Piggy Rainwater Bank [8]. The system collects rainwater, transports it, and uses it at a designated place. The facility has a screen that can be unfolded to collect rainwater and folded upon days without rain. This rainwater harvesting facility can solve water shortage problems in areas with small amounts of rainfall by allowing the collected rainwater to be reused. Purifying the rainwater occurs in the storage tank. Any contaminants deposited at the bottom of the rainwater storage tank outside can be discharged by siphoning which prevents any chance for oviposition by mosquitoes.

3.2. Approaches for improving sanitation and water resources

For reducing the potential for mosquito-borne diseases, our approaches in developing countries consisting of public buildings and individual houses are twofold. First, the combination of rainwater harvesting and eco-toilets can be installed in public buildings. Second, the integration of the rainwater collection facility and the WPPT offer significant improvements in sanitation for individual houses. These two approaches are presented in Figs. 1 and 2 respectively.

3.2.1. Solution for challenges in public zones

As presented in Fig. 3, for public buildings such as schools, public offices or hospitals, a drinking water supply system can be designed with a rainwater harvesting system with a tank capacity of 10–30 m$^3$ that contains a water treatment system. This system can produce drinking water 5–10 times of the tank capacity annually, depending on the weather and roof condition.

Rainwater, if harvested and treated correctly, can be used as a sustainable water resource for reducing these water-related problems [9]. Studies have shown that rainwater harvesting management can be used as a sustainable method for both public and residential zones and several studies are done to promote models for storage volume as a function of rain intensity and frequency [10–14]. Looking again at the eco-toilets, these use a waterless sanitation system to separate urine and feces and then store this waste in special bio-reactors to be utilized as an organic fertilizer that increases food productivity. This system is estimated to use a minimal amount of water to service 100–200 people. Eco-toilets can be used to improve sanitation, while the rainwater harvesting system offers a sustainable drinking water supply.

The schematic of an integrated system for a public building is shown in Figs. 1 and 3. We developed three key elements that reduce the water or wastewater accumulation on the ground surface and provide a well-managed, multi-purpose pond, thereby

![Fig. 4. Solutions for Challenges in Residential Community Zones.](image-url)
reducing the risk of open defecation by using more advanced sanitation solutions. The system also produces drinking water by innovations applied to harvesting rainwater.

3.2.2. Solution for challenges in residential community zones

As presented in Figs. 2 and 4, water and sanitation for individual houses can be improved considerably by installing an integrated system consisting of a smaller rainwater harvesting system (0.5–1 m$^3$), called a piggy rainwater bank, integrated with a soak-away infiltration system and WPPTs. This combined system provides a sustainable sanitation option for each family and ends the practice of open defecation.

Outside, collected surface rainwater is directed through sloped soil surfaces into a pond (area: 50–200 m$^2$, depth 1.0–1.5 m) as shown in Figs. 2 and 4. The piggy bank water system is designed to be a simple all-in-one and plug-and-play type that meets the WHO’s drinking water guidelines [8]. This system is tested and supplies high-quality water to the Vietnam residential areas as presented in Table 2 [10–12]. Communities could provide this self-supply system on their own without any difficulties. For individual houses, a drinking water supply and a dramatic improvement in sanitation are made possible by remodeling the roof to collect rainwater and building an infiltration system that is directed through a sloped soil surface.

### Table 3
Economic Analysis of an Example Case for the Newly Developed System for Public Zones. (Currency is US$).

<table>
<thead>
<tr>
<th>Water Practices</th>
<th>Options</th>
<th>Costs</th>
<th>Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Options</td>
<td>Costs</td>
<td>Problems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Construction Maintenance</td>
<td></td>
</tr>
<tr>
<td>Existing Practices</td>
<td><strong>Dams and Water Supply Pipelines</strong></td>
<td>Depends on the Distance and Availability</td>
<td>$1–2 for 20-l Bottle = $5000–10,000/Year</td>
</tr>
<tr>
<td><strong>Bottled Water</strong></td>
<td></td>
<td>Depends on the Distance and Availability</td>
<td>Depends on the Treatment Method</td>
</tr>
<tr>
<td><strong>Groundwater</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Building a Septic Tank</strong></td>
<td><strong>$40,000</strong> depended on the and Wastewater Treatment Plant Availability</td>
<td>$100/Year</td>
</tr>
<tr>
<td></td>
<td><strong>Eco-toilet</strong></td>
<td><strong>2–5 People</strong></td>
<td>Domestic Materials</td>
</tr>
<tr>
<td></td>
<td><strong>Rainwater Harvesting and Management System</strong></td>
<td>5–10 People</td>
<td>Domestic Materials</td>
</tr>
<tr>
<td></td>
<td><strong>Rainwater Piggy Bank</strong></td>
<td>0–5 People</td>
<td>Domestic Materials</td>
</tr>
</tbody>
</table>

### Table 4
Economic Analysis of an Example Case for the Newly Developed System for Residential Community Zones (Currency is US$).

<table>
<thead>
<tr>
<th>Sanitation Practices</th>
<th>Options</th>
<th>Costs</th>
<th>Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Options</td>
<td>Costs</td>
<td>Problems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Construction Maintenance</td>
<td></td>
</tr>
<tr>
<td>Existing Practices</td>
<td><strong>Open Defecation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Building a Septic Tank</strong></td>
<td><strong>$40,000</strong> depended on the and Wastewater Treatment Plant Availability</td>
<td>$100/Year</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Eco-toilet</strong></td>
<td><strong>2–5 People</strong></td>
<td>Domestic Materials</td>
</tr>
<tr>
<td></td>
<td><strong>Rainwater Piggy Bank</strong></td>
<td>0–5 People</td>
<td>Domestic Materials</td>
</tr>
</tbody>
</table>

j) This Table Presents Rough Data, Subject to Change Based on Real Site Situation.
in order to drain produced domestic greywater and reduce the potential of water accumulation on the ground. At the lowest place in a village, all the surface rainwater can be directed to a pond system (50–100 m² with a depth of 1.0 m). The pond should host fish and plants, making it a self-cleaning reservoir that is not suitable for oviposition of mosquitoes. This slope is designed for gathering the surface rain runoff. A mechanical cleaning mechanism can also be added if needed. Within these houses, the WPPT should be used which not only is made of eco–friendly materials, easy to move, install, and use, but also it is highly durable (load limit: 300 kg) and suitable for a family of one to five people [5,7]. The collected wastes of WPPTs can be treated and utilized as an organic fertilizer [7].

3.3. Economic analysis example of the developed systems

Tables 3 and 4 present our economic analysis example for the construction and maintenance of these newly developed systems in comparison with existing practices in public and residential zones. These tables present rough data, subject to change based on real site situation. These analyses show that our developed systems can solve the water and sanitation issues in an economical way [15]. The estimated values are valid for the aforementioned parameters summarized in Table 1 and yet may differ practically based on labor and material costs. Nonetheless, such sustainable practices have additional benefits such as increasing water self-efficiency, preventing or eliminating mosquito-borne disease breakouts and utilizing sanitary wastes as fertilizer. Therefore, they can be considered as appropriate substitutes for the current water and sanitation practices.

4. Conclusion

As is discussed, current water and sanitation practices can seriously increase the potential of the mosquito-borne disease breakouts as these practices provide suitable conditions for oviposition and reproduction of the mosquitoes. Providing correct water and sanitation management as a sustainable solution for this issue is much better than using insecticides or poor managed centralized water and wastewater systems.

To solve the problems of current practices, a new integrated system for sustainable access to hygienic and safe water and sanitation is proposed. This new technology will have significant outcomes in terms of the following aspects compared to current practices. With this newly integrated technology, water accumulating on the surface becomes runoff down a slope into a well-managed pond. This eliminates the hollows on the ground that collects rainwater and potentially prevents the oviposition. Also in places where open defecation is the only available sanitation practice, public eco-toilets will provide more suitable sanitation practices that produce fertilizer. Furthermore, whereas polluted water is unsafe to drink and can attract mosquitoes, rainwater is a safe drinking water resource.

Economic analyses show that the developed systems can solve the water and sanitation issues in an economical way as well as provide additional benefits such as increasing water self-efficiency, preventing or eliminating mosquito-borne disease breakouts and utilizing sanitized wastes as fertilizer.

In addition to the aforementioned benefits compared to existing or conventional technologies, our integrated technology will have critical outputs that save 2.5 billion people from suffering from any diseases caused by poor sanitation and the lack of access to clean water as a way to achieve Sustainable Development Goals (SDG–6). Nonetheless, further research is needed for assessments of the developed systems statistically in comparison with previous cases in local communities that did not have access to our technologies through periodic monitoring.

Acknowledgments

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