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Flood-risk vulnerabilities of sanitation facilities in urban informal settlements: Lessons from Kisumu City, Kenya

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Abstract

Flood disasters have increased in frequency and severity over the recent decades causing untold destruction to vulnerable physical infrastructure such as sanitation facilities. Factors including construction quality, design, siting, and users' behaviour further exacerbate the vulnerability of facilities. Despite this reality, very little has been done to document the extent of flood risk facing such facilities in the pro-poor urban informal settlements in developing countries. This study assessed the flood risks of vulnerable sanitation facilities in the urban informal settlements of Kisumu city, Kenya. The methodology involved assessment of sanitation facilities' flood vulnerabilities and assessment of flood risk models. Flood risk was assessed by estimating runoff from yearly rainfall totals and also by calculating storm return period and probability of exceedance. Vulnerability assessment for each sanitation facility was done by scoring against flood risk indicators ordered by weighted rank. The study observed that majority sanitation facilities in the urban informal settlements were considered "highly vulnerable" (57%). Flood risk analysis predicted growing vulnerability due to shorter storm return periods, especially under the RCP 8.5 scenario. It was established that over 20% of all rainfall events in the 50-year timeline had higher than 80% probability of exceedance rainfall, signifying higher storm risks. Additionally, the study showed that between 44% of rainfall received in the study area could translate to runoff, in the near future, further compounding flood risk predictions. With key informal settlements such as Nyalenda and Manyatta facing stronger future flood risks, general public health may be threatened, leading to increased social and economic instability on families and households. The study recommends adherence to improved toilet standards of construction and toilet-raising as methods of improving flood risk resilience and adaptation.

Keywords: *climate change, flood risk, informal settlements, Kisumu, sanitation, vulnerability*

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Introduction

Floods are the most frequent, recurring and devastating types of natural hazard facing the global society and accounting for approximately one third of all natural disasters in both the developed and developing worlds (UNISDR, 2017). In the past three decades, floods contributed to over 500,000 mortalities and resulted in more than US$500 billion of financial losses globally (Aitsi-Selmi *et al.,* 2015). Moreover, the pattern of floods has been changing, increasingly becoming unpredictable and intense due to climate change (Okaka, and Odhiambo, 2019; WMO/GWP, 2015). It is progressively evident that increased climate extremes and associated risks increasingly affect livelihoods of the majority poor vulnerable communities (UNISDR, 2017). In an urban setup, majority of the poor communities live within unplanned and often neglected neighbourhoods, with little coping strategies or ability to withstand extended climate severities. Studies done in Tanzania (De Risi *et al.,* 2013), Turkey (Tas *et al*., 2013), Ghana (Amoako, 2018), and South Africa (Williams *et al.,* 2018), all confirm to the common fact that urban informal settlements bear the greatest burden of urban flood risks. This situation is more true for Kisumu city where close to two fifths of the residents live within informal settlements (Simiyu *et al.,* 2017), a percentage higher than the national average.

A large number of informal settlements in developing countries are located in high risk areas such as low-lying lands and on riparian areas. This situation is caused by poverty and the failure by urban authorities to provide planned housing settlements to meet the growing demands of urban populations. Informal settlements have, in turn, developed into disaster risks hotspots, flooding being just one of them (Sakijege *et al.,* 2014). According to the Intergovernmental Panel on Climate Change (IPCC, 2014), exposed areas or urban centers lacking critical infrastructure and services are poised to experience amplified flood risks.

It is noteworthy however, that urban flood risk management must be cognisant of the various source of flooding in an urban area such as river flooding, coastal flooding, groundwater flooding and surface flooding – the type resulting from intense excess rainfall resulting in direct accumulation on gentle ground (De Risi *et al.,* 2013). By far, surface water flooding is responsible for a significant proportion of flood losses (De Risi *et al.,* 2013). This is because, under medium to extreme rainfall events, most of the flood water is expected to be carried as overland flow (Ferrari *et al.,* 2019) in which case the layout of surface pathways will largely dictate what areas of the urban terrain will be inundated.

In order to promote flood risk adaptation, recent research has focused on strategies such as mapping of flood-risk zones, assessment of damages to structures, economic impacts of flooding, governance and flood modelling (Nkwunonwo *et al.,* 2020; Al Baky *et al.,* 2019). While most of these strategies have been reactive to some extent, only tackling already existent problem; proactive approaches, based on projected risk scenarios, are more lauded in the wake of climate change (Amoako, 2018). Proactive approaches demand detailed knowledge through modelling of expected frequency, character, and magnitude of hazardous events in an area as well as the vulnerability of the people, infrastructures and economic activities in potentially dangerous areas.

So far, several methods have been employed to facilitate accurate estimation and prediction of floods (Nkwunonwo *et al.,* 2020), evolving from one dimensional models (1D) to complex two-dimensional (2D) models usually based on the shallow water equations (Al Baky *et al.,* 2019). To date, 2D modelling of urban floods is performed almost exclusively using digital elevation models (DEMs) and involving large computational power. A study by Moreta and Lopez-Querol (2017) used numerical experiments combining 2D shallow water model with extremely fine-resolution terrain data in the United Kingdom. Ferrari *et al.,* (2019) used a porosity-based numerical scheme for the Shallow Water Equations to model flood inundation in urbanized environments, while (Okaka and Odhiambo, 2019) on the other hand used a probabilistic and modular approach for calculating flooding risk in terms of the mean annual frequency of exceeding a specific limit state for each building within the informal settlement and the expected number of people affected. This study, therefore, assesses flood risk vulnerability of sanitation facilities in the urban informal settlements of developing countries with an aim of developing sustainable flood risk adaptation plans for urban development.

Vulnerability concept

The concept of vulnerability, according to WHO (2018) refers to a relative incapacity to endure the effects of unfavourable environment, while the same is described in the fourth assessment report (AR4) of the International Panel of Climate Change (IPCC) as the 'the degree, to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes (Sharma and Ravindranath, 2019; de Almeida *et al.,* 2018). As opposed to vulnerability, resilience is the ability of systems to absorb and recover from the impact of disruptive events without fundamental changes in function or structure, which depend on the flexibility and adaptive capacity of the system as a whole (Howard and Bartram, 2010). Resilient structures exhibit direct strength of structures when placed under pressure, such as flooding, to reduce their probability of collapse (Sharma and Ravindranath, 2019). Figure 1 illustrates a matrix classification of sanitation facilities with regards to vulnerability and adaptability (Howard and Bartram, 2010). According to Nasiri *et al.,* (2016), 'so many definitions of vulnerability appear in literature', proving this by highlighting eleven literature highlights defining vulnerability - among which is the United Nations version of 1982. This concept is reinforced by the IPCC outlook on the concept which has undergone significant reviews since 1992. A synthesis of the IPCC vulnerability concept approach has been done by Sharma and Ravindranath (2019). Nonetheless, the foregoing point to the fact that vulnerability measurement is complex, and often influenced by numerous environmental, economic, and social or political elements, and thus may vary from context and from community to another depending on circumstances.

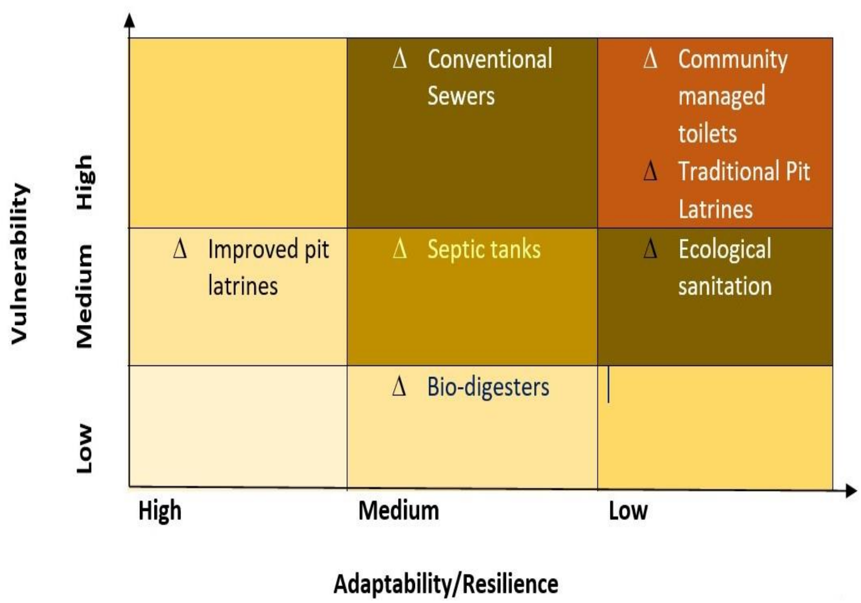

Figure 1. Vulnerability and resilience matrix for sanitation facilities

According to Huang *et al.,* (2012), vulnerability assessment methods are categorized in four distinct groups; indicator-based method, curve method, disaster-loss data method and the model method. In an earlier study, Deressa *et al.,* (2009) assessed household vulnerability to climate change by estimating the probability that a given shock or sets of shocks will move a household's income below the poverty threshold or force the income level to stay below the threshold. Rayhan (2010) employed a similar approach to estimate vulnerability to floods of households in Bangladesh. On their part, Fatemi *et al.,* (2020) applied a convergent mixed method to examine the physical vulnerability of buildings to recurrent flooding.

On a more local context, Okaka and Odhiambo (2019) assessed the health vulnerability of households living within the flood plains based on flood exposure, flood sensitivity, and flood adaptive capacity by scoring against different indicators. This was in line with the same indicator-based approach used by Ochola *et al.,* (2010) in assessing vulnerability of schools within the Nyando Basin (encompassing the study area) using a weighting and ranking technique. While all these approaches exhibit inherent strengths and weaknesses, depending on context, level of exposure and the type of community involved (Fellmann, 2012). Nasiri *et al.,* (2016) doing a comparative study to evaluate effectiveness of each of the four methods, settled on the indicator-based methods as a finer method in realizing effective policy change and driving community awareness - this informed the choice of indicator-based weighted vulnerability approach for this study.

For sanitation facilities such as pit latrines, indicators of vulnerability may include ability of the facility to endure and cope with floods. Therefore, factors such as type of latrine/facility, nature of superstructure and roofing, raising above ground, topography and slope, height of water table as well as existence of mitigation measures toward flood risks, account for the stability of sanitation facilities against flood waters. Evidently, flood waters can inundate poorly constructed and weak pit latrines or septic tanks (Othoo *et al*., 2020a). More about sanitation facilities and system characteristics may be reviewed from (Othoo *et al*., 2020b). Similarly, the hydraulic forces of floodwaters can rupture water-supply infrastructure while high sediment loads transported by floodwaters can reduce the efficiency of waste water treatment and cause system failures (Oates, 2014). Additionally, variations of the water table may lead to upwelling and backwashing of groundwater source leading to exposure to contaminants from pit latrines.

Materials and Methods

Study area

The study area encompassed five urban informal settlements of Nyalenda B, Nyalenda A, Manyatta B, Manyatta A and Obunga, and two peri-urban informal settlements of Kogony and Korando of Kisumu city. The city is located on the shores of Lake Victoria at longitudes 34°20′E and 34°70′E, latitudes 0°20′S and 0°25′S and at altitude of 1160 m which rises to about 1400 m above sea level (Simiyu *et al.,* 2017). Kisumu has an annual precipitation between 1111 and 1407 mm received in two major rainy seasons; March, April and May and October, November and December and a subdued rainfall peak in August (Wandiga *et al.,* 2007). Temperature varies seasonally with a mean annual temperature range of 18ºC to 20ºC. The hot and dry seasons fall in January and February while a cool and dry season exists in June and July (JJ).

The city is surrounded by hilly escarpment on the north, massive wetland covers to the southern lakeshore and two plain belts characterised by black cotton soils on the eastern region of the city (Wandiga *et al*., 2007). The soils of the plains are generally characterised by high water table, and the drainage conditions have largely influenced the quality and nature of onsite sanitation facilities in the area (Othoo *et al.,* 2020a, 2020b). Major water sources in the city include the lake, shallow wells, and springs. It's noteworthy that the Lake Victoria basin, where Kisumu City is located, is one of the most flood-prone lake-belt zones in Kenya (Wright *et al*., 2013; Opondo, 2013).

Sanitation Facilities data collection

The study used convenience sampling to document sanitation facilities after the methodology described in Othoo *et al.,* (2020a, 2020b). Data on type of facility, superstructure material used, roofing material, whether raised above the ground or not, nature of sharing between households, and materials used for slab, was collected. Topography, vegetation cover, water table height, as well as evidence of any flood mitigation measures undertaken by communities was noted for each site.

Climate data

Historical rainfall data for the period 1960 – 2016 was obtained from the Kenya Meteorological Department (KMD) for the Kisumu Meteorological Station upon request. Simulated rainfall data for Kisumu was downscaled from the Global Climate Models (GCMs) using the Coordinated Regional Climate

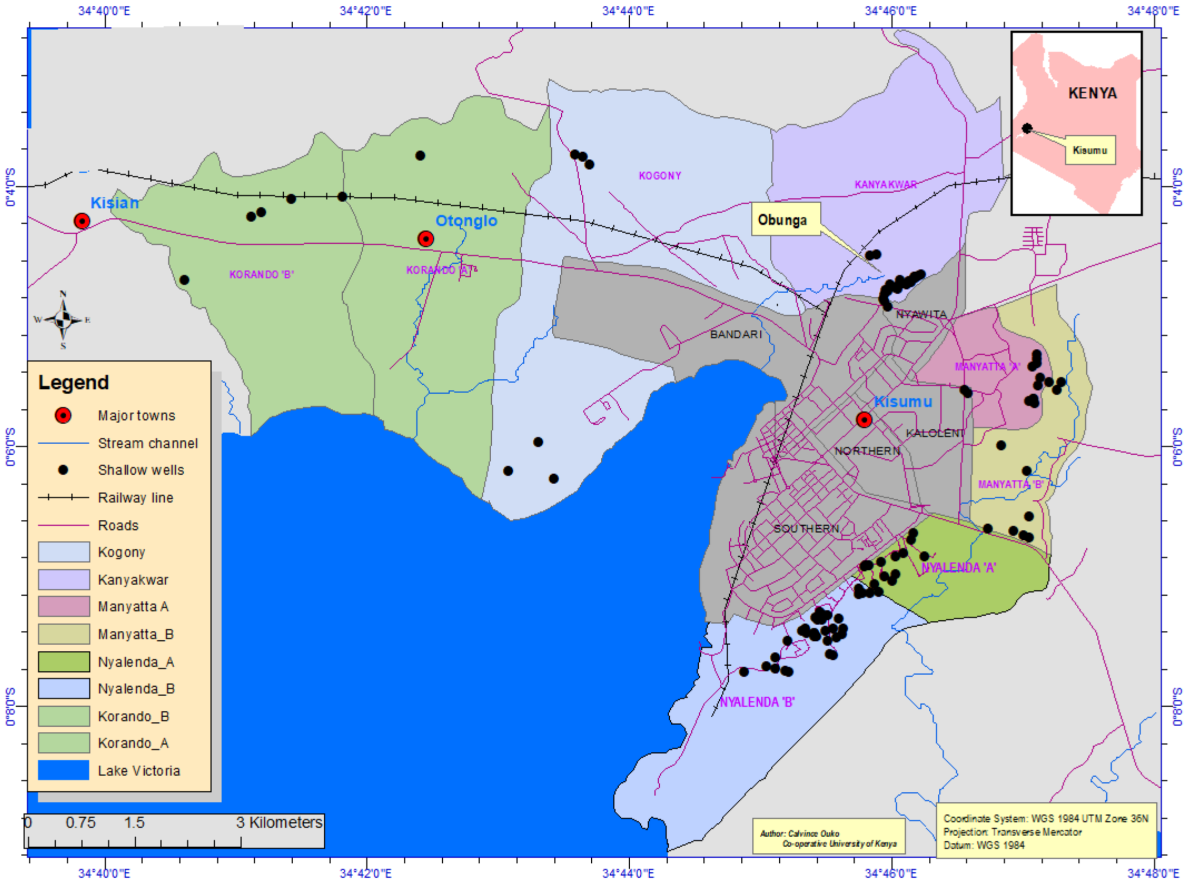

Figure 2. Map of the study area showing five urban informal settlements of Nyalenda A, Nyalenda B, Manyatta A and Manyatta B and Obunga and two peri-urban settlements of Kogony and Korando

Downscaling Experiment (CORDEX) for East Africa (Endris *et al.*, 2013). The African CORDEX domain covers 45.76°S to 42.24°N and 24.64°W to 60.28°E with a resolution of 0.44 degrees and employing ten Regional Climate Models (RCMs). Kisumu Data was downloaded from the Canadian Centre for Climate Modelling and Analysis (CCCMA), under the

365-day CanESM2 GCM (ensemble) domain covering a period from 2000 to 2050. The data was downscaled for the Representative Concentration Pathways (RCP) 4.5 and RCP 8.5 scenarios over the study area. Historical simulated dataset for the period 1971 to 2005 was used for bias correction (Fang *et al.*, 2015).

Data analysis

Sanitation Infrastructure Flood Vulnerability Assessment

Sanitation infrastructure vulnerability was assessed using a modified weighted and ranking technique (Table 1) adopted from a similar technique used by Ochola *et al.*, (2010). The methodology took account of important physical factors associated with flood risks in the study area. Sanitation facilities were evaluated based on selected vulnerability indicators (equation 1). The factors were partitioned into sub-factors, each assigned a ranking value score. The combined vulnerability index was summation scores from all sub-factors. The results from the weighted ranks was classified into three categories: vulnerable, marginally vulnerable and not-vulnerable. The vulnerability categories were then aggregated as; highly vulnerable (25 - 33), vulnerable (16 - 24), marginally vulnerable (7 - 15) and not vulnerable (1 – 6) based on the total aggregated vulnerability.

Sanitation infrastructure vulnerability = *f[F,W,R][C,S,W,D] [E],[SH] ………..……………..1*

F = Floor elevation,
W = Material used for wall construction and its present nature
R = Roofing material
C = Site/compound flatness
S = Soil type
W = Water table height
D = Distance from stream/river channel or flowing drainage
SH = Degree of sharing of facility
E = Evidence of flood mitigation efforts

Table 1. Flood risk vulnerability Assessment Summary for sanitation infrastructure

Vulnerability Factor	Weighting	Sub –factor	Rank
Types	1	TPL	4
	2	VIP	3
	3	Ecosan	2
	4	S/F	1
Roofing	1	Open	2
	2	Roofed	1
Body structure	1	Mud	5
	2	Iron-sheets	4
	3	Bricks	3
	4	Blocks	2
	5	Stones	1
Elevation	1	Not raised (= 0.0m)	3
	2	Slightly raised (elev. = 0.0 – 0.5m)	2
	3	Adequately raised (> 0.5m)	1
Soil types	1	Clay	3
	2	Sandy	2
	3	Stony	1
Flatness of surface	1	Flat	3
	2	Gentle	2
	3	Steep	1
Water table	1	High <3m	3
	2	Moderate 3 -5m	2
	3	Deep >5m	1
	1	Very near/within riparian	3
Distance from	2	Slightly far	2
stream/river	3	Not near	1
Facility Sharing	1	Highly shared >3HHS	3
	2	Slightly shared 1 – 3 HHS	2

	3	Not shared	1
Flood mitigation efforts	1	None	4
	2	Inadequate	3
	3	Moderately adequate	2
	4	Adequate	1

Climate Data Analysis

Data was analysed descriptively in MS Excel using Excel Pivotal table to group and organize the time series data into monthly and yearly statistics. The forecasted data was bias-corrected using simulated historical data using the Local intensity scaling (LOCI) technique (Fang *et al.*, 2015).

Flood Frequency Analysis

Flood frequency analysis and probability of storm exceedance were estimated for a 50-year period. The study used the yearly baseline rainfall total records from 1966 to 2015 and simulated data from 2001 - 2050. The return periods were plotted on the Intensity-Duration-Frequency (IDF) curve while the probability of storm exceedance was presented as percent of total rainfall for the year (Sabarish *et al.*, 2017; Ahmad, 2015; USDA, 1989). The following steps were involved;

a. Selection of the annual total rainfall of the selected 50-year duration from the 1965 – 2015 historical observed data, the same was done for the 50-year forecast duration.
b. Ranking the 50-year records in descending order to obtain frequency
c. Determination of the probability distribution of the annual rainfall totals. If n is the total number of values to be plotted and m is the rank of a value in a list ordered by descending magnitude, the exceedance probability of the m^{th} largest value, x_m, is computed:

$$x_m = \frac{Rank\ (m)}{n+1} \quad \text{……..2}$$

Calculation of the return period (T-yr) by using the following frequency factor equation:

$$T = \frac{1}{x_m} \quad or \quad \frac{(n+1)}{Rank(m)} \quad \text{……..3}$$

The frequency curve was plotted on a Log base axis against the yearly rainfall totals.

Estimation of urban runoff/flash flood by the Curve Number Method

For each of the annual rainfall totals, runoff was estimated using the Runoff Curve Number (CN) method developed by the United States Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS), and popularly known as the CN method. The CN method formulae and procedure is explained in literature (Sabarish *et al.*, 2017; Ahmad, 2015; USDA, 1989).

The run off depth Q (mm) was estimated through equation:

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \quad \text{……..4}$$

Where, P – basin average rainfall estimated from available rainfall records

S – potential maximum retention(mm) after runoff begins and is related to the soil and cover conditions

S – Computed from equation:

$$S = \frac{25400}{CN} - 254 \quad \ldots\ldots 5$$

The runoff curve number (CN) was estimated (CN = 90) from the provided tables in Appendix A of the USDA Hydrology Training Manual Series 104 (USDA, 1998). The Antecedent Moisture Content (AMC) was assumed at average condition (AMC-II) while the hydrologic soil type was type D which typically describes soils of most of urban informal settlements in Kisumu (Opondo, 2013).

Results

Four major types of facilities were identified in the area, namely; ventilated improved pit latrine (VIP), traditional pit latrine (TPL), septic tank and flush (S/F), and ecological sanitation (Ecosan) facilities (Figure 3).

Analysis of Sanitation Types and Characteristics

Traditional pit latrines dominated the urban informal settlements (in this case; Nyalenda B, Nyalenda A, Manyatta B, Manyatta A and Obunga) where they constitute as much as 70% of total sanitation facilities within these areas. The largest number of VIP was observed in the peri-urban informal settlements (Kogony and Korando). There were about 3%, 1%, 4%, 3%, and 2% Ecosan facilities in Nyalenda B, Nyalenda A, Manyatta B, Manyatta A, and Obunga, respectively.

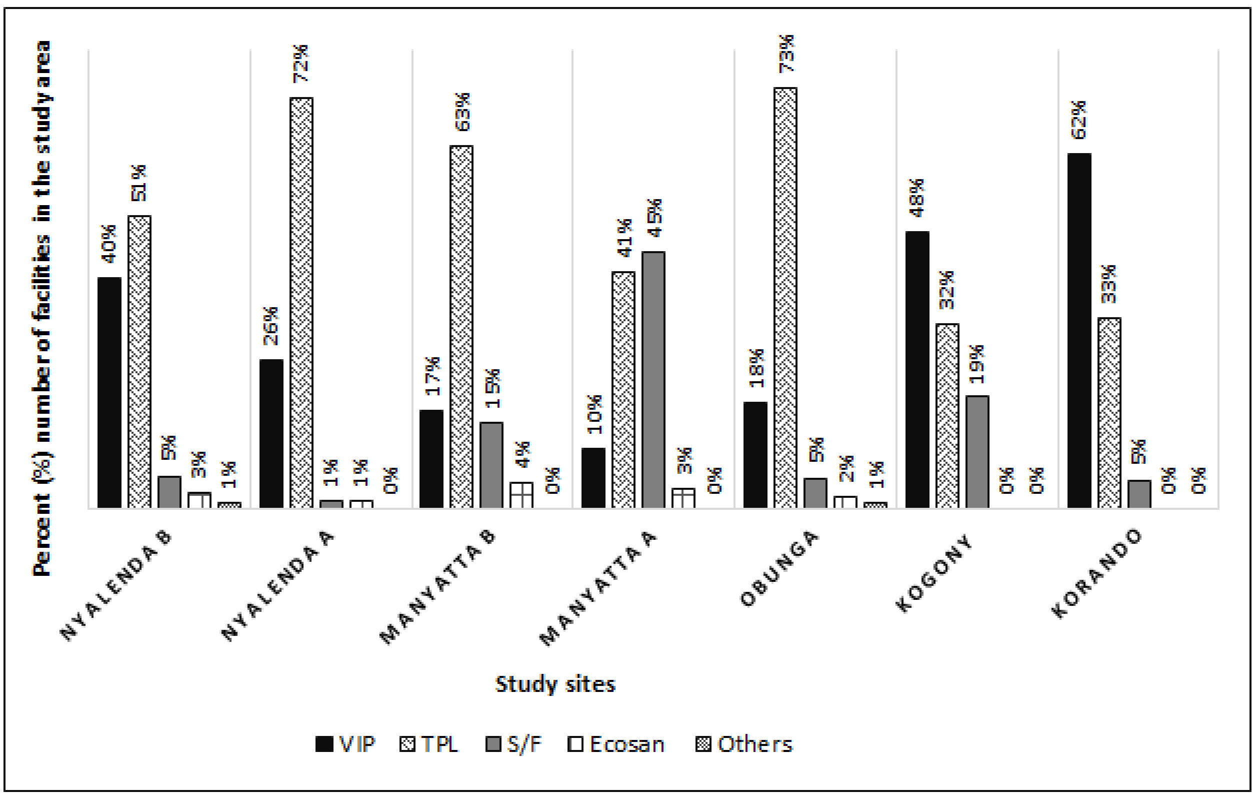

Figure 3. Types of sanitation facilities in the study area

The TPLs were characterised by poor construction, poor body structure (superstructure) quality and shallow depths (Figure 4), this was evidenced by the numbers that lacked adequate concrete walls and roofing cover. A considerable number of TPLs' superstructures were made of iron sheets (Nyalenda A = 42%, Nyalenda B = 32%, Manyatta A, Manyatta B, and Obunga 35%, 32% and 42%, respectively). In the urban slums, about 40% of the TPLs had open or no rooftops. Ventilated improved pit latrines (VIPs), being more improved than TPLs, were observed with better superstructure and roofing, this was the case also for Ecosan and S/F facilities.

Figure 4. Examples of sanitation facilities within the urban informal settlements of Kisumu

The study further established different flood mitigation measures undertaken in the area; for instance, approximately 73% of all VIPs studied were raised as a method of mitigation against flood effects. Similarly, about 53% of the TPLs were raised above flood heights, with areas such as Nyalenda A, Nyalenda B and Manyatta B, recording higher numbers of of TPLs with raised structures. The average raising height for facilities was calculated at approximately 0.25 m - 0.5 m across the study area. Nonetheless, improperly sited facilities were observed to be important flood risk challenge, for example the facilities found to exist on poorly drained topography (Figure 4), and even along riparian areas. Concerning depth of latrines, the study found that most latrines (95%) have pit depths ranged between 0.25 m - 4.0 m except in Kogony and Korando (peri-urban) where they were relatively deeper (4.0 m -10.0 m depth). Proximity analysis revealed high density of pit latrines with about two and four pit latrines within 15.0 m and 30.0 m radius to water sources in the urban slums.

Sanitation Facilities Flood Risk Vulnerability Assessment

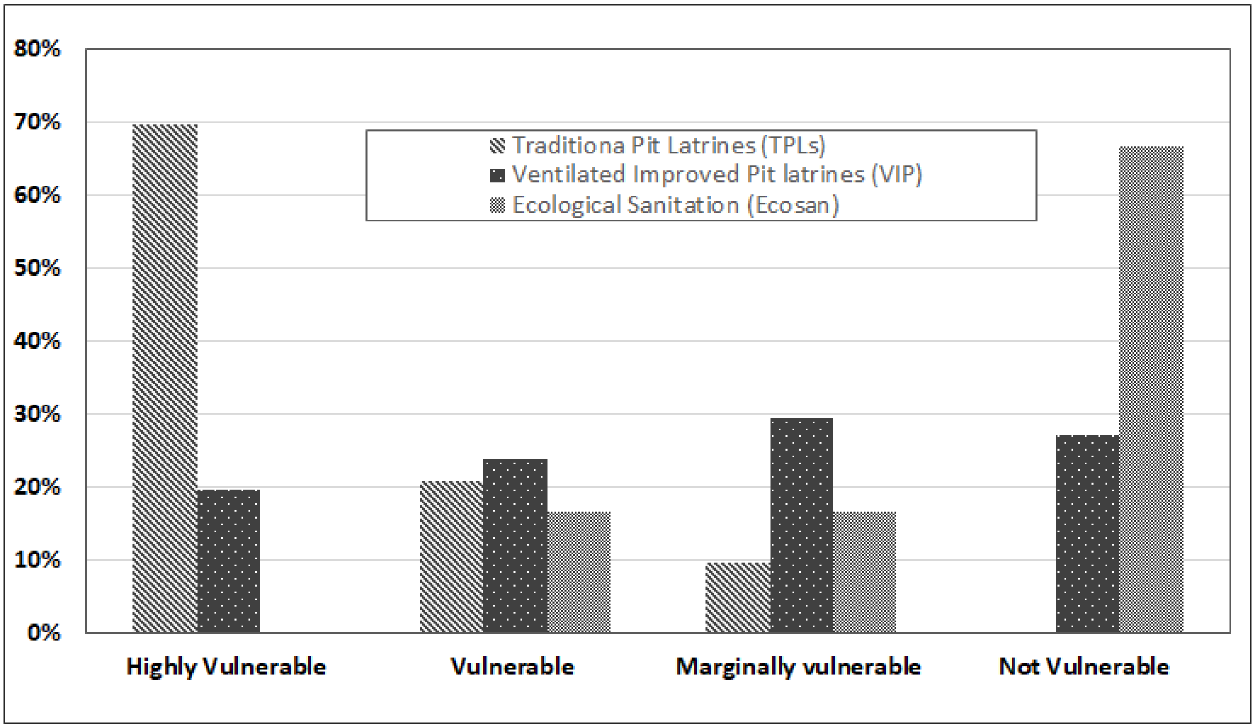

Figure 5. Vulnerability assessment by sanitation facility types

Figure 5 show the vulnerability assessment results for different sanitation types, the results show that majority of TPLs were in the "highly vulnerable" category, while most Ecosan facilities were not-vulnerable. Only about 18% of VIPs were in the "highly vulnerable" group, it was further observed most facilities reported as "highly vulnerable" were relatively higher in the urban slum areas (61.5%) that in the peri-urban areas (about 22%). Analysis of vulnerability further established (Figure 6) that about 81%, 86%, 100%, 64%, and 54% of all sanitation facilities in Nyalenda B, Nyalenda A, Manyatta B, Manyatta A, and Obunga, respectively, existed within areas with more than 50% probability (Moderate and High-flood risks) of flooding during medium and above-normal rainy season – riparian flood plains. With projected growth of urban slums, more facilities could exist in the highly flood risk zones as more settlements encroach into the riparian areas.

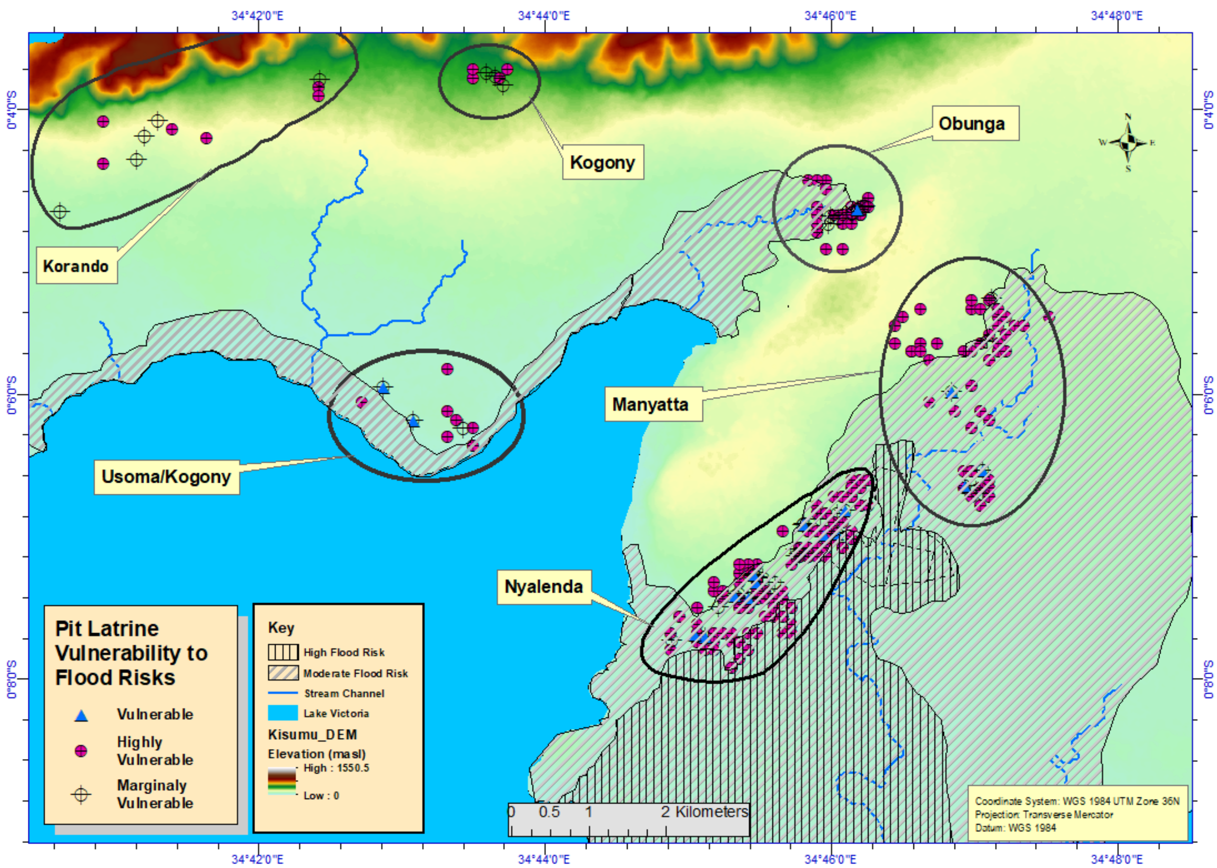

Figure 6. Spatial Plots of vulnerable facilities and flood risk zones within the study sites, the circled area showing the distribution of sanitation facilities relative to identified flood risk zones

Analysis of Flood Risks

Three factors were analysed in this section; probability of exceedance, the storm return period, and run-off trends for the baseline and future scenarios (Table 2). The lowest rainfall amount was recorded in 2014 (993.6 mm) while 1968 recorded the largest rainfall amount (1791.0 mm). The return period (*T*) for the rainfall amount 1310.3 mm (1966) is 1.6 years, meaning, it is likely to repeat every 1.6 years. It can be seen that the largest rainfall amount (1791.0 mm in 1968) might only recur after 51 years (T = 51.0 years), while the probability that this rainfall amount would be exceeded is 2%. About 22% (397.9 mm) of the rainfall received in 1968 translated into runoff in that year. There is also a likelihood that rainfall amount 1029.1 mm (1973) or 993.6 mm (2014) would recur every year, with probability of exceedance of 96% and 98%, respectively. Rainfalls with shorter return periods and higher probability of exceedance signify higher flood risk; out of the 50 rainfall events (50-year timeline) there are 10 events of higher than 80% probability of exceedance, all of which have less than 1.5 return period. As far as runoff is concerned, the lowest run-off amount generated was in 1968 (22%) while highest yearly runoff was recorded in 1973 (65%).

Figure 7 shows a rainfall intensity distribution frequency curves (IDF) for 50-year period from 2001 – 2050 under two climate projection scenarios (RCP 8.5 and RCP 4.5). Representative Concentration pathway (RCP) scenario 8.5 is the "business as usual" human behaviour, with no intervention or mitigation efforts, while RCP 4.5 entails somewhat intermediate interventions. The results show, for instance, about 12 mm rainfall per day with a return period of three years under RCP 8.5 while under RCP 4.5, the return period will be six years. The figure (Figure 7) projects that rainfall amounts of about 5.0 mm daily (approximately 1825.0 mm yearly) is likely to recur every year between 2001 and

2050, while a doubled amount is likely to recur every two years under the same period. Considering the estimated run-off potential of 44%, the 5.0 mm yearly rainfall is likely to translate to 1.1 mm or 3.25 mm run-off annually.

Analysis of the probability of exceedance across different months (Table 3) revealed that future scenarios will have higher exceedance values than the baseline, except for the months of March, May, July and August for RCP 4.5, and April, June, July and August months for RCP 8.5. At the 80% probability of exceedance, April, the wettest month in the baseline period, would have decreased exceedance amounts, while drier months like January and February would have increased exceedance amounts.

Discussion

Vulnerability analysis revealed that most sanitation facilities in the informal settlements, especially the urban informal settlements, are facing increased flood risk owing to their state of construction, nature of water table and general surface conditions. As previously stated, many informal settlements (slums) exist within potentially high flood risk zones (Othoo *et al.,* 2020a). This fact was true of the study area as shown in many recent studies (Othoo *et al.,* 2020a; Sabarish *et al.,* 2017; Opondo, 2013) where some areas have higher water table, supposedly rising to depths of 3.0 m below ground level.

Generally, existing human and structural vulnerabilities in pro-poor settlements are known to exaggerate disastrous impacts of floods on sanitation infrastructure (Okaka and Odhiambo, 2019). The Presence of weak superstructure, for instance, iron sheet superstracture as opposed to stone or bricks, contributes to structural weaknesses against runoff and winds (Okaka and Odhiambo, 2019; Okurut *et al.,* 2015). It is for this reason that facilities that demonstrated high quality construction/protection, such as ecological sanitation (Ecosan) – see Figure 1, ranked among the least vulnerable. Unlike the Ecosan, TPLs had inherent weaknesses that contributed to higher vulnerability, for instance; lack of adequate roofing, resulted in direct pounding of rainfall, leading to faster fill-up, while continuous exposure to sunshine contributing to weakening the superstructure. It was clearly established (Figure 3) that most vulnerable facilities dominated poorer urban slums where socio-economic vulnerabilities rank high (Simiyu *et al.,* 2017) as opposed to the peri-urban areas where economic livelihoods are relatively higher (Simiyu *et al.,* 2017). This perhaps may indicate that the quality and nature of facilities constructed is largely dependent on the level of affordability as driven by the prevailing social and economic factors. This fact was reinforced by the fact that majority of the well-constructed latrines (such as Ecosan) were reported interventions from non-governmental organizations (NGOs). It is generally concluded that continued improvement in community

Table 2. Calculated storm return period (T), probability of exceedance and estimated runoff (Q

Year	Annual rainfall Totals (mm)	Return Period T=(m+1)/rank (Yrs)	Probability of Exceedance (%)	Run-off Q(mm)	Runoff (%)
1966	**1310.3**	**1.6**	**55%**	**557.0**	**43%**
1967	1225.7	1.4	73%	588.2	48%
1968	**1791.0**	**51.0**	**2%**	**397.9**	**22%**
1969	1218.1	1.3	75%	591.0	49%
1970	1282.6	1.7	59%	567.1	44%
1971	1335.9	2.0	51%	547.7	41%
1972	1453.8	3.2	31%	506.3	35%
1973	**1029.1**	**1.0**	**96%**	**664.6**	**65%**
1974	1195.8	1.2	80%	599.4	50%
1975	1252.4	1.5	65%	578.2	46%
1976	1276.1	1.6	61%	569.5	45%
1977	1566.0	7.3	14%	468.6	30%
1978	1765.7	25.5	4%	665.5	38%
1979	1468.8	3.4	29%	501.1	34%
1980	1106.3	1.1	92%	633.9	57%
1981	1118.4	1.1	90%	629.2	56%
1982	1448.2	2.8	35%	508.2	35%
1983	1145.0	1.2	86%	618.9	54%
1984	1231.1	1.4	71%	586.1	48%
1985	1352.6	2.2	45%	541.7	40%
1986	1376.4	2.4	41%	533.3	39%
1987	1294.4	1.8	57%	562.8	43%
1988	1421.8	2.7	37%	517.3	36%
1989	1368.6	2.3	43%	536.0	39%
1990	1172.6	1.2	84%	608.3	52%
1991	1337.1	2.0	49%	547.3	41%
1992	1250.6	1.5	67%	578.9	46%
1993	1137.9	1.1	88%	621.6	55%
1994	1502.6	4.6	22%	489.7	33%

1995	1451.7	3.0	33%	507.0	35%
1996	1540.2	6.4	16%	477.1	31%
1997	1610.7	12.8	8%	454.0	28%
1998	1185.6	1.2	82%	603.3	51%
1999	1511.3	5.1	20%	486.7	32%
2000	1214.9	1.3	76%	592.2	49%
2001	1491.5	4.3	24%	493.4	33%
2002	1618.5	17.0	6%	451.5	28%
2003	1252.4	1.6	63%	578.2	46%
2004	1476.1	3.9	25%	498.6	34%
2005	1065.6	1.1	94%	650.0	61%
2006	1318.8	1.9	53%	553.9	42%
2007	1202.7	1.3	78%	596.8	50%
2008	1343.8	2.1	47%	544.9	41%
2009	1404.3	2.6	39%	523.4	37%
2010	1476.1	3.6	27%	498.6	34%
2011	1587.9	10.2	10%	461.4	29%
2012	1524.9	5.7	18%	482.2	32%
2013	1246.0	1.5	69%	580.6	47%
2014	**993.6**	**1.0**	**98%**	**630.0**	**63%**
2015	1583.1	8.5	12%	463.0	29%

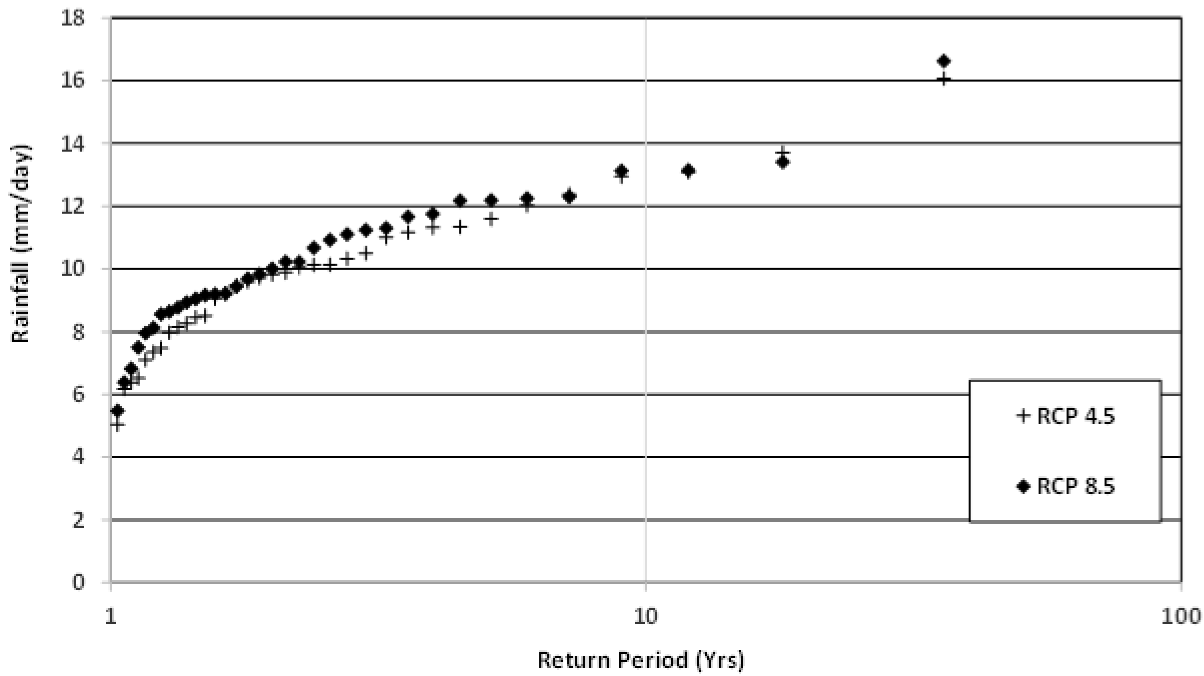

Figure 7. Rainfall frequency and return period for simulated period

Table 3. Probability of Exceedance Table calculated at 80% probability for the baseline period (1961 -2010) and RCP periods (2001-2050)

	Probability of Exceedance (mm) calculated at 80% probability		
Months	**Baseline**	**RCP 4.5**	**RCP 8.5**
JAN	29.2	46.9	55.3
FEB	31.3	50.2	68.8
MAR	98.7	**86.6**	120.7
APR	**137.6**	140.4	**124.6**
MAY	104.0	**84.0**	91.2
JUN	51.8	100.7	**35.5**
JUL	27.6	**15.0**	**16.4**
AUG	47.5	**33.9**	**30.8**
SEP	54.4	72.7	88.1
OCT	54.4	103.9	88.2
NOV	64.0	119.5	91.1
DEC	54.9	100.2	108.4

Moreover, future flood risk was observed from the proportion of rainfall amounts recorded above 80% probability of exceedance estimated. Probability of exceedance is a statistical metric describing the probability that a particular value will be met or exceeded (Sabarish *et al.*, 2017) and is widely used to evaluate the chance of occurrence of a given rainfall amount useful in flood management plans (Douglas *et al.,* 2008). Similar to the storm return period, the study also noted higher probability of exceedance for RCP 8.5 than RCP 4.5, meaning, a greater likelihood of higher rainfall amounts above the 8th percentile (80% probable rainfall amounts) under the "business as usual", minimal mitigation case (IPCC, 2014). This is also a case against countries and planners to embrace meaning mitigation measures instead of the uncontrolled business-as-usual models for emissions.

With the noted vulnerabilities and predicted flood risks likely to increase, this study has significant implications to developing countries experiencing urban informal challenges and the risk of flooding in such urban slums. First, in areas where flood risks are high, improving sanitation facilities structural quality and strength could be a valuable strategy towards the adaptation to floods and pounding surface runoff. Normally, structures designed to cater for potential probability of occurrence of extreme rainfall during their lifetime remain resilient during such unfortunate events (IPCC, 2014). Kazi and Rahman (1999) notes that stability of sanitation infrastructure is the ability to withstand the worst-case predicted flood extremes, and this study already established a considerable proportion (44%) of all rainfall received could translate to runoff volumes in the future. It is more devastating if such floods recur within shorter intervals and more severely.

The social, economic and health impacts arising from flood risks cannot be overstated! Floods may topple and destroy weak and poorly constructed sanitation facilities along the paths of the draining water flow, this may lead to physical destruction, as well as overflow of pit latrine contents into the flood water, affected residence within such environment may remain exposed to contamination arising from the polluted water and this may threaten public health. In a slum environment, this might have far-reaching consequences are residence often lack good adaptive strategies besides the weak economic livelihoods that may reduce quick and adequate access to health support, thus exacerbating the spread of the impacts. Again, floods may continuously corrode concrete or earthen-walled facilities, thereby reducing their lifespan and exposing them to pollution which may promote water borne diseases in these already vulnerable urban settlements (WMO/GWP, 2015). Destroyed infrastructure would mean more resource need for raising new ones and renovation, which is an additional burden on the already economically vulnerable communities. Therefore, more structurally stable, on-site sanitation facilities – preferably made from strong concrete slabs and reinforced pits - should be promoted in these flood-prone urban cities.

Moreover, stability of structures may also be enhanced by raising facilities above ground or above flood water height. Besides the added stability, raising toilet facilities ensure the toilet slab is elevated above flood height or possible surface runoff levels, this is helpful in ensuring flood waters don't fill-up pit latrines to overflow. The concept of raised pit latrines have been widely documented and recommended in flood prone environments (Okaka and Odhiambo, 2019; Othoo *et al*., 2020b). Several studies have endorsed the use of raised facilities in developing countries (Nakagiri et al., 2015; Oates *et al*., 2014; Khisa *et al.,* 2013; Morshed and Sobhan, 2010; Dzwairo *et al.,* 2006). According to Kazi and Rahman (1999), the correct solution to the problem of latrine flooding is to construct a "raised latrine". This study, thus observes that raising sanitation facilities to a height of 0.25 m - 0.5 m above present flood height may potentially be helpful in combating near future flood risks.

Additionally, the study notes that location of facilities near riparian areas, or on high flood risk zones, increases vulnerabilities (Figure 6), there is a clear indication that the nearer the riparian area the more the vulnerability of sanitation facilities to floods. In this study, some study areas such as Nyalenda B and Nyalenda A had close to 70% of total sanitation facilities surveyed existing within "high flood risk" zones. Prohibition of settlements along the riparian areas, may also be key to the safety and sustainability of sanitation infrastructure. With the increasing rates of urbanization in developing countries, and the overstretching urban capacity to provide housing and critical amenities such as water and sewerage, the informal settlements would continue to grow and reliance on base sanitation systems will persist. There are fears that the expanding slum settlements would continue to infringe on the more fragile, flood risk zones such as marshlands and flooded plains as these areas rarely have government-controlled settlements plans.

Conclusion and Recommendations

This study intended to assess existing flood risk vulnerability on sanitation facilities in the urban informal settlements of Kisumu and provided specific flood risk resilience planning which are replicable across other urban slums facing similar challenges globally. Motivated by the fact that physical infrastructure (i.e. sanitation facilities) vulnerabilities associated with climate change continues to soar globally and poor urban informal settlements in developing countries are at greatest risk, this study aspired to offer solution to poor urban communities living in the urban informal settlements. The methodology involved assessment of sanitation facilities' vulnerabilities using a weighted indicator-based method, and assessment of flood risks from estimated runoff, calculated storm return period and probability of exceedance.

The results showed that majority sanitation facilities in the urban informal settlements were considered "highly vulnerable" (57%). Further, the flood risk analysis predicted growing vulnerability due to shorter storm return periods, and higher probability of exceedance, especially under the RCP 8.5 scenario. The results indicate a need for enhanced mitigation and adaptation interventions to improve flood resilience for each sanitation facility in the informal settlements, an observation informed by the predicted increase in future flood risk as indicated by increased storm return period, runoff levels and probability exceedance amounts. Unabated, flood inflicted impact on vulnerable sanitation facilities may directly translate into humanitarian risks and threaten public health leading to increased social and economic instability on families and households. The study recommends improved standards of construction and toilet-raising as methods of improving flood risk resilience and adaptation for sanitation facilities among other climate-smart recommended practices.

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