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Key Points:
- Low-rise areas in Singapore show denser drainage networks that are conducive for breeding of dengue vector compared to high-rise areas
- Singapore urban plan to afford public housing in agglomerations of high-rise buildings does not increase the risk of dengue transmission
- City planners should consider the density of drainage networks for both the prevention of flooding and also the breeding of mosquitoes

Supporting Information:
- Supporting Information S1
- Table S1
- Figure S1
- Figure S2
- Figure S3

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Patterns of Urban Housing Shape Dengue Distribution in Singapore at Neighborhood and Country Scales

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Abstract Dengue is the most important human arboviral disease in Singapore. We classified residential areas into low-rise and high-rise housing and investigated the influence of urban drainage on the distribution of dengue incidence and outdoor breeding at neighborhood and country scales. In Geylang area (August 2014 to August 2015), dengue incidence was higher in a subarea of low-rise housing compared to high-rise one, averaging 26.7 (standard error, SE = 4.83) versus 2.43 (SE = 0.67) per 1,000 people. Outdoor breeding drains of *Aedes aegypti* have clustered in the low-rise housing subarea. The pupal density per population was higher in the low-rise blocks versus high-rise ones, 246 (SE = 69.08) and 35.4 (SE = 25.49) per 1,000 people, respectively. The density of urban drainage network in the low-rise blocks is double that in the high-rise ones, averaging 0.05 (SE = 0.0032) versus 0.025 (SE = 0.00245) per meter. Further, a holistic analysis at a country-scale has confirmed the role of urban hydrology in shaping dengue distribution in Singapore. Dengue incidence (2013–2015) is proportional to the fractions of the area (or population) of low-rise housing. The drainage density in low-rise housing is 4 times that corresponding estimate in high-rise areas, 2.59 and 0.68 per meter, respectively. Public housing in agglomerations of high-rise buildings could have a positive impact on dengue if this urban planning comes at the expense of low-rise housing. City planners in endemic regions should consider the density of drainage networks for both the prevention of flooding and the breeding of mosquitoes.

Plain Language Summary Dengue is among the increasing public health problems to many countries, especially in large urbanized areas. Various climatic and nonclimatic factors interact and shape the disease distribution in endemic cities. In Singapore, types of urban housing influence indoor breeding and dengue cases. The strategic plan of Urban Redevelopment Authority of Singapore focuses on affording public housing in high-rise buildings as a solution for the growing population. In this study, we revisit this observation at a neighborhood and country levels categorizing urban housing of Singapore into low-rise and high-rise housing. A low-rise housing subarea at the neighborhood shows more outdoor breeding in drains and denser drainage network compared to high-rise subarea. At the country scale, risk of dengue is related to the fractions of area or population living in low-rise housing. The distribution map of dengue incidence shows a similar profile to the distribution maps of low-rise housing. This finding suggests that the government strategic plan to afford public apartments in urban agglomerations of high-rise buildings does not increase the risk of dengue transmission. On the other hand, the higher risk in low-rise housing is likely related to more conducive factors for indoor-outdoor breeding habitats.

1. Introduction

Dengue is among the reemerging human arboviral diseases in the world (World Health Organization (WHO), 2009). The disease incidence has increased thirtyfold during the last 50 years, placing half of the global population at risk, mainly in its endemic territories in Asia, Latin America, and some foci in Africa (Bhatt et al., 2013; Seidahmed et al., 2012; WHO, 2009). Epidemics of dengue and other related arboviruses (i.e., Chikungunya & Zika Virus) are expanding at higher rates (Adam et al., 2016; Chadee & Martinez, 2016; Mayer et al., 2017). The economic burden of dengue is enormous particularly in Southeast Asia and Americas (Shepard et al., 2011, 2016; Shepard et al., 2013). The annual cost of 58.4 million symptomatic cases ranges between 3.7 and 19.7 billion US$ (Shepard et al., 2016). Indeed, various climatic (e.g., temperature, rainfall, and relative humidity which affect the vector competence) and nonclimatic factors (e.g., herd immunity, dengue serotype, and genotype) interact on regional and local scales and seem to be responsible for this increase in epidemics (Halstead, 2008).

Clustering of dengue—in space and time—is a common observation in endemic areas (Mammen et al., 2008; Vazquez-Prokopec et al., 2010; Yoon et al., 2012). Dengue cases usually aggregate within a close distance ranging from 100 to 800 m (Bowman et al., 2014). Some of this clustering is attributed to the short flight dispersal (i.e., usually $<$100 m) of the primary vector *Ae. aegypti* (Harrington et al., 2005), affecting the man-vector contact.

In underplanned urban centers, inadequate water supply, poor sanitation, and disuse of nonbiodegradable containers lead to *Aedes* breeding in storage containers inside houses (Bowman et al., 2014; Caprara et al., 2009; Seidahmed et al., 2012). On the other hand, in well-planned urban areas, *Aedes aegypti* breeds in various indoor habitats such as plant pots, bamboo pole holders, and tanks of air conditioners (Goh, 1997; Hammond et al., 2007; Halstead, 2008). Further, there is growing evidence for vector adaptation to outdoor breeding habitats (Chadee & Martinez, 2016; Manrique-Saide et al., 2012) or seasonal shifts between rain-fed and human-made containers in urban areas (Becker et al., 2014). The outdoor breeding habitats in urban settings include roof gutters, discarded receptacles, sewage, and storm drainage networks (Barrera et al., 2008; Manrique-Saide et al., 2012; Montgomery et al., 2004; Montgomery & Ritchie, 2002). Outdoor breeding habitats of *Ae. aegypti* can form not only near housing but also in public venues such as schools, restaurants, and workplaces (Garcia-Rejon et al., 2011; Ooi et al., 2001). Outdoor breeding habitats in urban hubs and dengue epicenters can possess a risk for outside transmission of dengue, affecting both residential and visiting populations.

Dengue is an endemic disease in Singapore. Despite intensive control efforts to keep the population at a low risk of dengue, incidence has steadily increased since the 1990s. Three major dengue outbreaks struck Singapore in 2004–2005, 2007, and recently in 2013–2014 (Hii et al., 2009; Koh et al., 2008; Ng et al., 2015). Both switches in dominant DENV strains and introductions of new virus genotypes have been considered as triggers for these outbreaks (Lee et al., 2012).

Dengue mosquito species *Ae. aegypti* and *Ae. albopictus* are sympatric in Singapore. However, *Ae. aegypti*, which is the primary vector, predominates in urban areas and shows a better vectorial competence for dengue transmission in the city (K. L. Chan, Chan, & Ho, 1971; Kek et al., 2014). Also, dengue virus was more detected in specimens of *Ae. aegypti* than *Ae. albopictus* in Singapore (Chung & Pang, 2002). One of the key control strategies is to scale up community participation in removing/destroying indoor breeding habitats of *Ae. aegypti*. This policy has resulted in a significantly low ($<$1%) house index (HI), which is the percent of domiciles with indoor breeding containers for *Aedes* (Egger, 2008).

The relationship between urban housing and dengue in Singapore was first documented in the 1960s (Y. C. Chan et al., 1971). At that time, slum houses showed the highest HI for *Ae. aegypti*, while flats at multistory buildings had the lowest one. During the last 50 years, a progressive urban planning has changed the face of Singapore and slum houses had vanished. The strategic plan of Urban Redevelopment Authority (URA) of Singapore focuses on affording public housing in high-rise buildings as a solution for the growing population and scarcity of the land. Annual reports of the Ministry of Health (MOH) show a difference in dengue cases and incidence between three types of accommodations: HDB flats, compound houses, and condominiums (Viennet et al., 2016). However, further research is needed to investigate the impact of the urban planning and urban housing on magnitude and distribution of dengue in the country.

In this study, we classified the urban housing in Singapore by the height of buildings into low-rise (i.e., less than or equal to three floors) and high-rise housing. The high-rise buildings consist mainly of public housing owned by Housing and Development Board (HDB) and private condominiums (condos) for middle and upper classes. In contrast, the low-rise houses contain various types of landed private properties such as bungalows, shophouses, and terraced houses. Figure 1 shows a difference in HI between low-rise and high-rise housing during the period 2000–2015, 95% confidence intervals (CIs) [1.38, 2.81] and [0.32, 1.07], respectively. While low-rise housing accommodates only 6% of households in Singapore, the odds of an indoor breeding of *Aedes* in this type of accommodation is 3.1 times that in a high-rise one (95% CI = 2.9–3.3). Also, these vector control surveys—carried out by the National Environmental Agency (NEA)—show that domestic containers top the indoor breeding habitats for *Ae. aegypti* (NEA, unpublished data, 2015).

This study explores the influence of the pattern of urban housing on dengue distribution at a neighborhood and country scales. In a previous survey in Geylang between August 2014 and August 2015, we found that *Aedes aegypti* breeds mainly in clogged drains close to the housing (Seidahmed & Eltahir, 2016). These

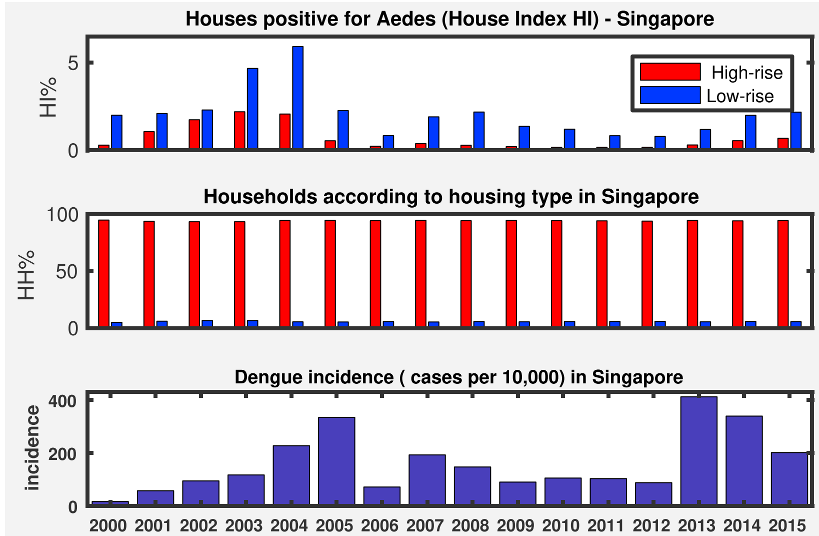

Figure 1. (a) House Index% (HI) of *Aedes* breeding in low-rise (95% CI [1.38, 2.81]) and high-rise (95% CI [0.32, 1.07]) areas; (b) households% living in low-rise and high-rise housing, and (c) dengue incidence in Singapore (2000–2015). (Data source: MOH, NEA, and DOS (Singapore))

outdoor breeding habitats are clustered in the low-rise housing part of the Geylang. We document here a clustering of dengue cases in the same low-rise subarea. The low-rise portion has a denser urban drainage network. The outdoor abundance of *Ae. aegypti* (i.e., pupal density and trapped adults) shows a similar spatial difference. A further spatial analysis for the whole country revealed that dengue incidence is proportional to the fraction of low-rise housing. Likewise, the drainage network is denser in low-rise residential areas than high-rise ones. The strategic urban plan of Singapore to afford public housing in urban agglomerations of high-rise buildings does not increase the risk of dengue in Singapore.

2. Materials and Methods

2.1. Biosafety and Ethics Statement

This study received a risk assessment approval from the Institutional Biosafety Committee of Singapore-Massachusetts Institute of Technology (MIT) Alliance for Research and Technology. The research was not conducted in any private residences, and no human samples were collected.

2.2. Neighborhood

Geylang [1.3206°N, 103.8869°E] is one of the historic areas of the city. It is a hyperendemic area with a continuous circulation of the four serotypes (Y. C. Chan et al., 1971; Liew & Curtis, 2004). For this study, we selected an area that extends from Pan Island Express to Guillemard Road (from north to south), and from Paya Lebar Road to Sims Way (from east to west). It has a roughly rectangular shape of 1.9 × 1.1 km^2. Due to observed differences in the landscape of the built-up area, the study area is divided into two subneighborhoods: low rise (area = 1.19 km^2) and high rise (area = 0.9 km^2). The East-West Mass Rapid Transit line roughly separates landed low-rise private houses (mainly shop houses) to the south from high-rise housing to the north (see Figure 2).

2.3. Urban Housing Data

We obtained spatial housing data from Singapore Land Authority (SLA). This data set includes built-up area by type of utility (i.e., commercial, industry, and housing by type of buildings). Also, we used OpenStreetMap data to retrieve locations and length of roads by category (e.g., highways and residential) in Singapore.

Two fishnets were created using ArcGIS 10.2: (1). A neighborhood fishnet of 10 × 7 regular grids having 200 m^2 each block and (2) country fishnet of 14 × 11 blocks of 1 km^2 resolution. The fishnet was geographically rotated to fit the study domain. For the country-scale analysis, we calculated the fraction of low-rise housing as the built-up area of low-rise houses divided by the total residential area in that block.

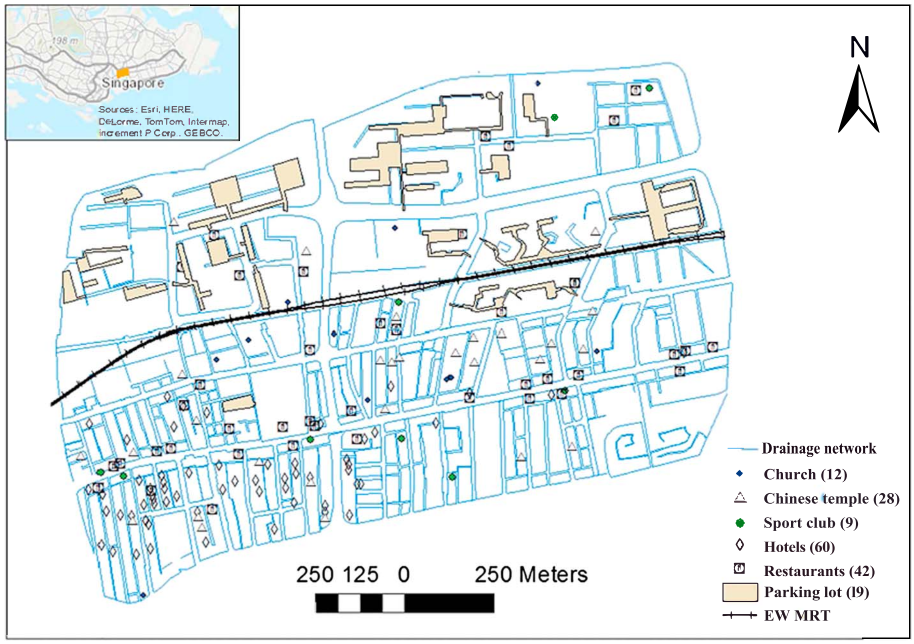

Figure 2. A sketch shows locations of hotels, Chinese temples, restaurants, and the urban drainage network in Geylang neighborhood.

2.4. Population Data

Demographic data 2014 were obtained online from the Department of Statistics (DOS) of Singapore. The data set includes population by subzone and type of housing (HDBs, condos, and landed houses). We projected the population distribution in each grid cell of the country and neighborhood fishnets.

The cadastral map of Singapore was obtained from Singapore Land Authority (SLA). This data set gives the footprints of buildings by utility type (i.e., residential and nonresidential) and numbers of floors. Hence, SLA shapefiles for residential buildings at the neighborhood and country maps were extracted and spatially linked to the DOS population data using common attributes of subzone and utility types of buildings. Also, living area of residential buildings was calculated multiplying the building footprint's area by the associated number of floors. To estimate the population at each building, the proportion of living area was multiplied by the total population of the subzone. The fraction of the population living in each housing type (i.e., low rise and high rise) of a grid cell was obtained by dividing numbers of inhabitants in this housing type by total residents of that block.

Further, anecdotal evidence suggests more nonresidents exist in the low-rise housing. For example, because of low rental rates, foreign workers lodge in the shop houses. To test the effect of this assumption on dengue, we projected two population scenarios in the Geylang neighborhood: (1) a fixed population of only residents and (2) dynamic population including nonresidents and visitors. Further details on estimation procedures of population distribution are shown in supporting information Text S1.

2.5. Dengue Data and Calculations of Dengue Incidence

Two epidemiological data sets were obtained for this study: (1) dengue cases in Geylang neighborhood (2010–2015), received from the Ministry of Health (MOH), Singapore; this data set includes the number of reported cases by location (i.e., street address) and epidemiological week for the period; and (2) dengue cases in Singapore (2013–2015), retrieved mainly from a recent report by Hapuarachchi and others (Hapuarachchi et al., 2016). This article provides the spatial distribution of dengue in 2013–2014 using four quantiles of cases densities: two cases/km^2, 16–25 cases/km^2, 56–61 cases/km^2, and >217 cases/km^2. We used ArcGIS 10.3 to digitize these maps and extract the data sets for 2013 and 2014. All data sets were gridded in ArcGIS. The weighted average for quantiles of dengue density in a block was calculated before that was transformed into the number of cases. Also, dengue cases in 2015—obtained from MOH—were georeferenced and aggregated by their corresponding 1 km^2 blocks.

We calculated dengue incidence as the number of cases in the grids divided by sum of the projected population in that grid. Incidence rates were laid over 3-D maps for the study area. To generate a 3-D map for dengue incidence in the Geylang, a triangulated irregular network was created in ArcScene 10.4, and the height of each building was calculated by multiplying the number of floors by 2.6 m ceiling height (i.e., the minimum clearance height standard by HDB). Then, the disease incidence was overlaid on the horizontal surface of the gridded map.

2.6. Entomological Data

Entomological data were collected during a recent survey carried out between August 2014 and August 2015 in the Geylang. Outdoor breeding habitats were inspected twice weekly, and active outdoor habitats of *Ae. aegypti* and *Ae. albopictus* were georeferenced. Inspectors had regularly investigated the drainage system of Geylang for pupae and larvae of these two species. Specimens sampled from positive drains *were transferred* to *the laborat*ory and identified using taxonomic keys (Huang, 2002; Mattingly, 1971; Rueda, 2004). We calculated pupal density per 1,000 population by dividing estimates of *Aedes* pupae found in a grid cell by the total human population in that grid. Further details on this entomological survey can be found in (Seidahmed & Eltahir, 2016).

Besides, a total of 16 gravitraps were randomly placed outdoors in the two subareas of Geylang. The traps were inspected weekly for the presence of adults of dengue vector. Trapped adults on the inner film of the adhesive board were sorted out and identified using taxonomic keys (Rueda, 2004).

2.7. The Density of Urban Drainage Network

We delineated the urban drainage network (the system of conduits) at the neighborhood and country scale. Observations from the field confirmed that roads could surrogate the drainage system in Geylang. Among categories of roads in OpenStreetMap data, we found that residential and service roads match the drainage network in the urban housing areas of Singapore. This finding was further examined by random field visits to residential areas, locations of water sensors and images of Google Earth.

Locations of water sensors and closed-circuit televisions (CCTVs) were used to confirm that roads are a good surrogate for mapping the drains. A total of 208 water level sensors, and 49 CCTVs are used by Public Utility Board (PUB) to monitor the drainage system of Singapore. Also, a random sample of 100 streets names was navigated in Google Earth to verify the estimation of drains by roads. Further, satellite images of Google Earth were used to correct the data and exclude roads that are unsuitable for mapping the drainage network (i.e., where drains do not follow the roads perimeters).

The length of the conduits of the network in each block was summed.

The following equation calculates the density of the urban drainage network in each block:

$$\text{Drainage density}\left(\text{m}^{-1}\right) = \frac{\text{Conduits length}\ (\mathscr{M})}{\text{housing area}\ (\text{m}^2)}$$

Furthermore, the ratio of the drainage density in the low-rise to high-rise areas was calculated in the 1 km^2 blocks. A buffer zone of 30 m was created in ArcGIS around residential buildings and according to housing type. The ArcGIS intersection tool was used to identify overlapping drainage perimeters. Conduit lengths were aggregated in each housing, area and the drainage density was calculated using the above equation.

2.8. Hot Spot Analysis

This technique was previously employed in several epidemiological studies of dengue (Jeefoo et al., 2011; Khormi et al., 2011). In this work, we used Optimized Hot Spot Analysis (Getis-Ord Gi*) tool of *ArcGIS* 10.2 to identify significant hot spot grids of dengue occurred between 2010 and 2014, and whether these hot spots showed a difference between the low-rise and high-rise subareas.

The following equation gives the statistic:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j}x_i - \overline{X}\sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2}{n-1}}}$$

where x_i is dengue cases in block j, $w_{i,j}$ is the spatial weight between two blocks, n is the total number of the blocks. The following equations determine the average ($\overline{X}$) and variance (S):

$$\overline{X} = \frac{\sum_{j=1}^{n} x_i}{n}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_i^2}{n} - \left(\overline{X}\right)^2}$$

The analysis compares the local sum of dengue cases in a location (and its surrounding) to the expected sum of cases in that location. The expected sum of cases was calculated using an epidemiological window. We selected two weeks and a diameter of 200 m for the epidemiological window based on an autocorrelation ArcGIS tool. An inverse distance approach was employed to generate the spatial weight matrix wij. This chosen strategy is appropriate to measure clustering of dengue cases or breeding habitats of the vector. The procedure allows considering the effect of distance between pairs of locations on dengue clustering. The wij matrix is a two-dimensional (N_x) array that represents each N feature by one column and one row.

The Global Moran's *I* index was used to measure autocorrelation between the locations of dengue cases. The Moran's *I* index uses a range [−1, 0, 1] to verify tendency of the distribution toward dispersal, random, and clustering patterns, respectively. The peak of clustering intensity (i.e., cold and hot spots) was determined by the maximum value of standard deviation, *Z* score. A null hypothesis for a complete spatial randomness (CSR) was tested under $p < 0.05$ for the distribution of dengue cases within the Geylang area. The test was adjusted for spatial dependence using false discovery rate (FDR) correction method (Caldas de Castro & Marcia Singer, 2006).

Accordingly, a grid was identified as a hot spot if it has a larger *Z* score ($Z > 1.96$) and its *p* value <0.05. On the other hand, blocks of cold spots were identified if tested grids have small *Z* score ($Z < -1.96$) but they are also significant ($p < 0.05$). Further details on Optimized Hot Spot Analysis can be obtained online (ESRI. ArcGIS Resources: Optimized Hot Spot Analysis (Spatial Statistics); 2016) and in Ord & Getis (1995).

3. Results

3.1. Influence of Urban Housing on Dengue Clustering at a Neighborhood Scale

3.1.1. Dengue Incidence (August 2014 to August 2015)

A total of 353 cases was reported in the Geylang between August 2014 and August 2015. More dengue cases occurred in the subarea of low-rise houses than in the high-rise one. Using the fixed and dynamic population projections, average of dengue incidence per 1,000 population in low-rise versus high-rise blocks, was 26.7 (standard error, SE = 4.83) versus 2.43 (SE = 0.67), and 7.93 (SE = 1.4) versus 1.74 (SE = 0.36), respectively (see Figure 3a). Further, chi-square test shows a significant difference ($p < 0.001$) between the reported and expected dengue cases in the low-rise and high-rise blocks, using the fixed and dynamic population projections (Table 1).

3.1.2. Dengue Entomology

3.1.2.1. Pupal Density Per Population

The total of *Aedes* pupae was 2,066: 1,690 were *Ae. aegypti*, 1,730 from drains, and 1,870 were found in the low rise. By gridding locations of breeding habitats, 27 blocks were positive for *Ae. aegypti* compared to 9 blocks for *Ae. albopictus*. Besides, 77.8% ($n = 28$) of the positive blocks appear in the low-rise subarea. The average pupal density of *Aedes* in Geylang was 171.5 pupae per 1,000 population, considering a fixed population. Interestingly, the pupal density of *Ae. aegypti* shows a similar difference between low-rise and high-rise subareas of Geylang. These are 246 (SE = 69.08) and 35.4 (SE = 25.49) per 1,000 population, in the low-rise and high-rise blocks, respectively (see Figure 3b). The correlation between the dengue cases and the total of pupae per block was insignificant (Pearson's $r = 0.13$, 95% CI = −0.13–0.37).

3.1.2.2. Outdoor Adult Mosquitoes

A total of 83 adult mosquitoes was trapped in Geylang between October and December 2015. *Culex* and *Ae. albopictus* dominated the collection, 33 and 32, respectively. However, there were 7 out of 10 of the traps in the low-rise subarea were found positive for *Ae. aegypti* or *Ae. albopictus* compared to three out of 6 of the

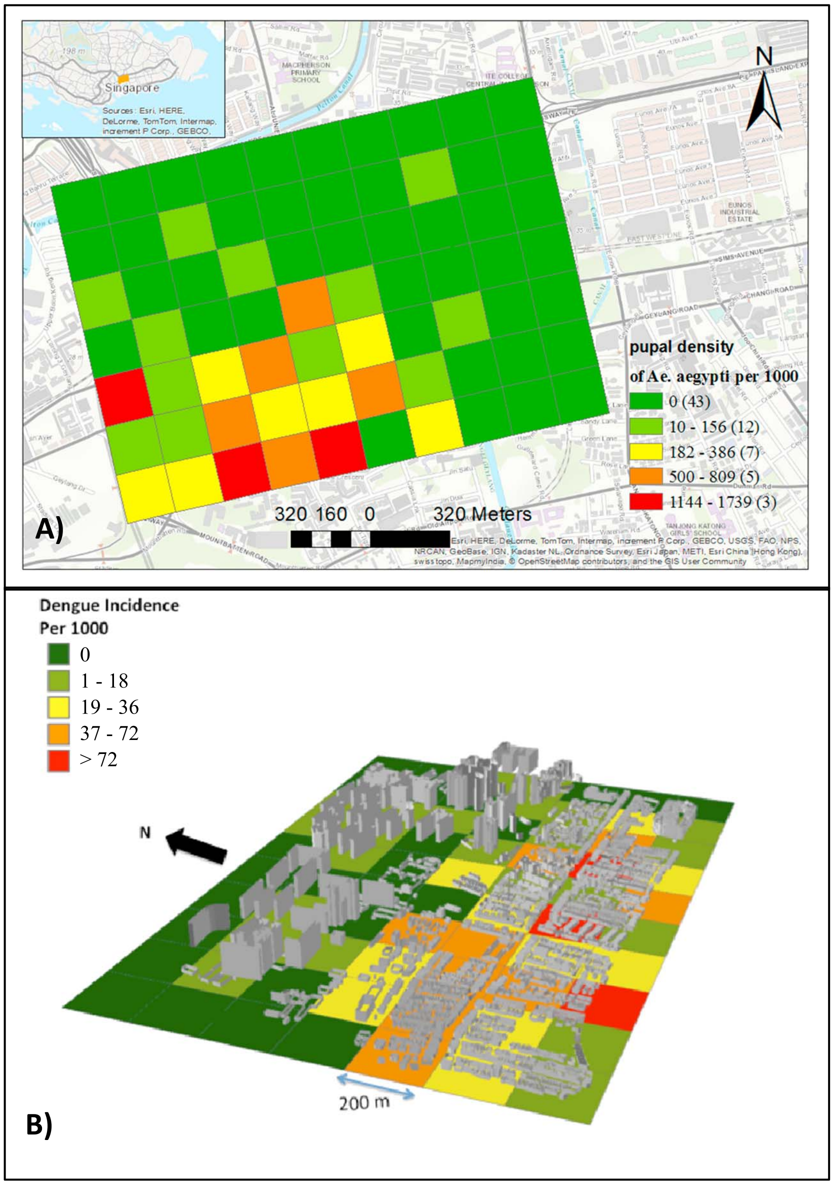

Figure 3. (a) Dengue incidence per 1,000 in Geylang August 2014 to August 2015. (Disease data source: MOH, Singapore) (b) Annual pupal density in Geylang. Annual pupal density per 1,000 population in 200 m^2 blocks (August 2014 to August 2015).

Table 1
Observed and Expected Dengue Cases Using Estimates for Fixed and Dynamic Populations in Geylang, Singapore (August 2014 to August 2015)

			Dengue vases		
Category	Subarea	Projected population	Observed	Expected	Chi-square test
Fixed population	Low-rise	14,159	310	153.28	χ^2 = 154.54, d.f. = 1, $p < 0.001$
	High-rise	18,448	43	199.72	
	Total	32,607	353	353	
Dynamic population	Low-rise	38,698	310	211.34	χ^2 = 71.59, d.f. = 1, $p < 0.001$
	High-rise	25,940	43	141.66	
	Total	64,629	353	353	

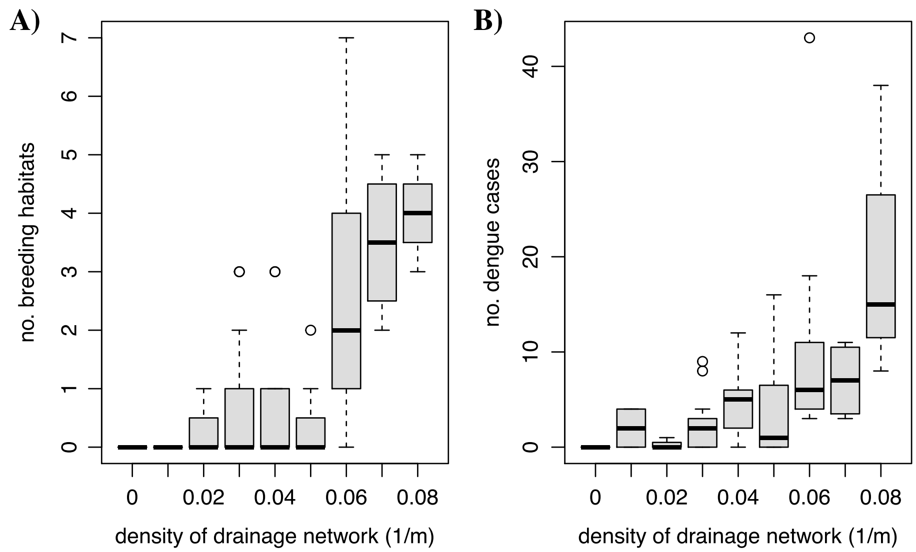

Figure 4. (a) The density of the drainage network in a block versus the total of breeding sites of *Aedes aegypti*, Geylang-Singapore (August 2014 to August 2015); (b) density of the urban drainage network in a block versus dengue cases, Geylang-Singapore (August 2014 to August 2015).

traps placed in the high-rise one. Also, 88.8% (16 out of 18) of caught females of *Ae. aegypti* were found in the low-rise subarea. In contrast, 87.5% (28 out of 32) of trapped females of *Ae. albopictus* were in the high-rise section where a lush greenery surrounds the HDBs. Collections of the gravitraps are in supporting information Table S1.

3.1.3. Density of the Drainage Network and Other Urban Features in Geylang

The density of the urban drainage network is higher in the blocks of low-rise subarea than in high-rise one, averaging 0.05 (SE = 0.0032) versus 0.025 (SE = 0.0025) per meter. This difference in means is significant using *T* test (95% CI = 0.01–0.024, p = 0.00014). There is a moderate positive correlation between the number of breeding habitats of *Ae. aegypti* and density of the urban drainage network in Geylang (Pearson's $r = 0.57$, 95% CI = 0.38–0.72, $p < 0.001$), (see Figure 4a for the box plot). The correlation is positive but weak for the total of pupae (Pearson's $r = 0.34$, 95% CI = 0.1–0.55, $p < 0.001$). Further, the correlation between the urban drainage network and dengue cases is also positive (Pearson's $r = 0.5$, 95% CI = 0.29–0.67, $p < 0.001$), (see Figure 4b).

The high-rise subarea is also characterized by parking lots ($n = 17$ versus only two in the low-rise subarea, total area = 103,914 m^2) and bounded by greenery surroundings in the northern and western sides. Further, we observed that public buildings such as hotels, restaurants (including coffee shops), schools, and houses of worship mainly aggregate in the low-rise area (see Figure 2).

3.1.4. Persistence of Dengue Difference in Geylang (2010–2013)

A total of 1,068 dengue cases was reported in Geylang between 2010 and 2013. Cumulative incidence between 2010 and 2013 was more in the low-rise blocks than the high-rise subarea (average 98.6 versus 10.1) (see Figure 5). Moreover, blocks of the former subarea had experienced more notification weeks of dengue cases during the 4 year period (average 30.3 versus 4.5 notified weeks) (see supporting information Figure S1).

3.1.5. Cold and Hot Spots in Geylang

Dengue cases in Geylang are statistically clustered using Moran's *I* index ($I = 0.26$). Moran's *I* index showed the highest significant magnitude when the epidemiological window is 200 m within two epidemiological weeks (*Z* score = 12.7; $p < 0.001$).

Neglecting the temporal aspect, analysis of incremental spatial autocorrelation shows that the highest *Z* score of clustering is obtained when the average distance between these cases is 200 m (see supporting information Figure S2). For the fixed population scenario, a total of 14 blocks is identified to represent significant dengue hot spots (with ≥90% confidence interval). Among these, 13 blocks clustered in the low-rise subarea, mainly in the left part of the low-rise area (see supporting information Figure S3).

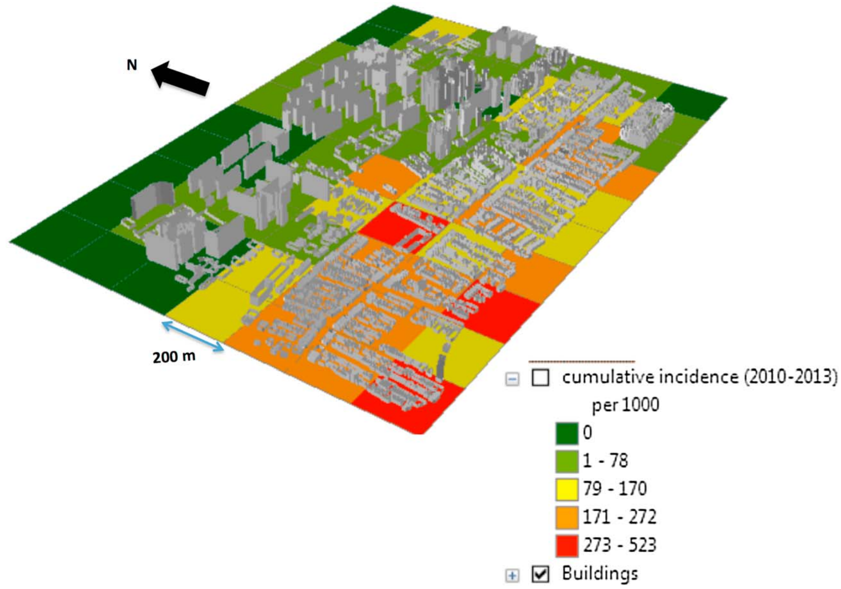

Figure 5. Dengue cumulative incidence per 1,000 in Geylang 2010–2013. (Disease data source: MOH, Singapore)

3.2. Influence of Urban Housing on Dengue Distribution at a Country Scale

The Singapore resident population of 3.87 million (as of 2014) is living in a total built-up area of 25.98 km^2. Out of 349 residential grids of 1 km^2, 52 and 175 are purely composed of people living in high and low-rise buildings, respectively. Population density per 1 km^2 in Singapore is shown in supporting information Figure S4.

3.2.1. Urban Housing and Population Distribution in Singapore

Figure 6a and Figure 6b show fractions of the area and people living in low-rise grids. The figure confirms that the population is concentrated in high-rise housing in Singapore. The high-rise neighborhoods are in the northeastern part of the island.

3.2.2. Distribution of Dengue Incidence and Urban Housing

Figure 6c shows average dengue incidence for 2013–2015 in Singapore. As expected, the disease incidence is higher in low-rise blocks mainly in the central region of the city. Also, dengue incidence increased as the fraction of the area of low-rise housing increased during the years: 2013 [R^2 = 0.31, $p < 0.001$], 2014 [R^2 = 0.38, $p < 0.001$] and 2015 [R^2 = 0.3, $p < 0.001$], see Figure 7a.

Similarly, the fraction of the population living in low-rise buildings has positively correlated with dengue incidence during the same period: 2013 [R^2 = 0.46, $p < 0.001$], 2014 [R^2 = 0.54, $p < 0.001$] and 2015 [R^2 = 0.48, $p < 0.001$], see Figure 7b.

3.2.3. Urban Drainage and Urban Housing

Figure 8 shows that average of drainage density in low-rise housing is 4 times that density in high-rise building areas, 2.59 and 0.68 per meter, respectively. This difference in means is significant using *T* test (95% CI = 0.65–3.16, p = 0.0029). The ratios of the drainage density in low-rise /high-rise in 1 km^2 blocks largely increase (more than 25 times) when the fraction of low-rise housing area exceeds 50% of the block area, see supporting information Figure S5.

4. Discussion

This study quantifies the impact of patterns of urban housing on dengue incidence and distribution in Singapore at a country and neighborhood levels. Our findings suggest that the strategic housing plan of URA does not increase the risk of dengue transmission in the country. The expansion of high-rise public housing will rather have a positive impact on dengue control if this urban planning comes at the expense of the built-up area or population living in low-rise housing.

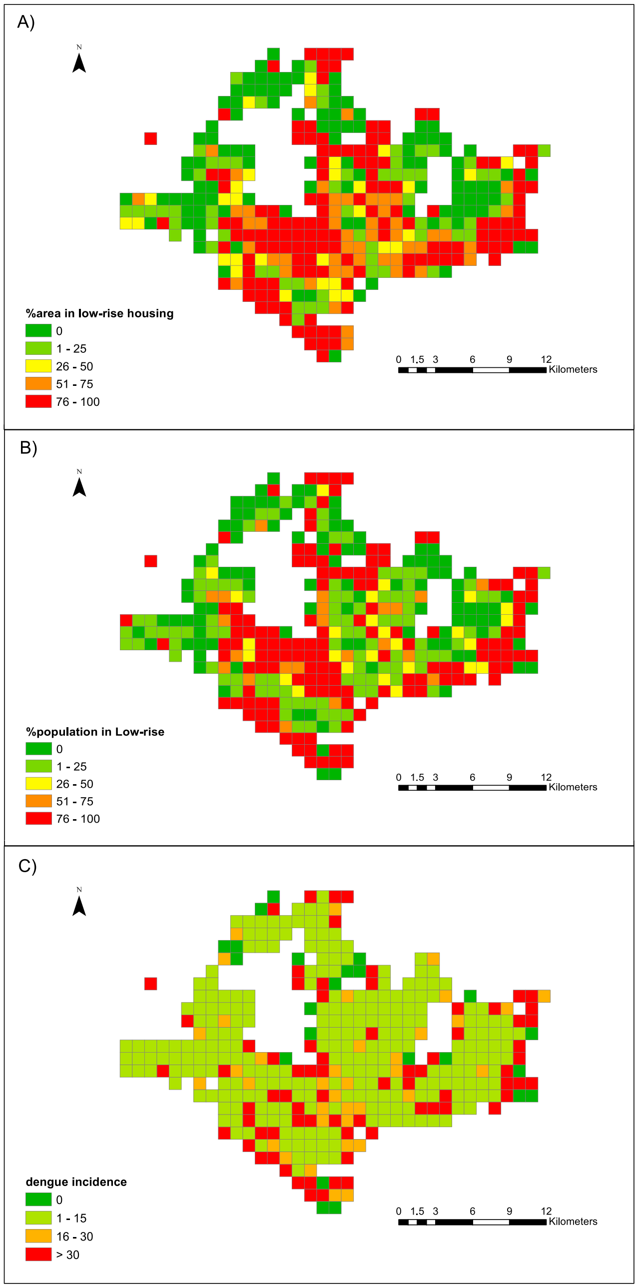

Figure 6. (a) Percent area of low-rise housing per 1 km^2 blocks in Singapore, (b) percent resident population living in low-rise housing per 1 km^2 blocks in Singapore, and (c) dengue incidence per 1,000 population in Singapore (2013–2015).

In the 1960s, researchers had reported a greater spatial spread for breeding of *Ae. albopictus* over *Ae. aegypti* in Geylang area (K. L. Chan, Ho, & Chan, 1971). They attributed this relative dispersal to Kallang basin serving at that time as refusal dump and large breeding swamp for this species. In contrast, *Ae. aegypti* had mainly infested indoors and primarily in low-rise neighborhoods composed of shop houses. The shop houses are still featured in conserved areas like Geylang and Little India; they are preserved because of their historical/architectural value to the country. Moreover, the growing affluent population of Singapore may prefer other types of landed houses instead of apartments in high-rise buildings.

The relationship between the incidence and area (or population) fraction of accommodation type implies that clustering of dengue between the housing types has more influence on dengue distribution than other factors underlying clustering within specific housing types. Hence, either community practices—conducive for indoor breeding—are being different between low-rise and high-rise neighborhoods or that conductivity for indoor and outdoor breeding habitats and their interactions are pertinent to the urban structure of the low-rise areas more than the community practices. Indeed, several socioeconomic factors could influence the community practices toward dengue. A previous study had revealed a difference in education and employment at households between hotspots and non–hot spot of dengue in Singapore (Ong et al., 2010). However, landed houses were the non–hot spots in that study, having higher education and employment rates. Further research is needed to answer whether there is a more knowledge-practice gap on dengue control by the community in low-rise housing, or that this type of accommodation intrinsically favors breeding of the vector indoor and outdoor.

We also showed that density of the urban drainage system has a positive correlation with the number of dengue cases and breeding habitats at the neighborhood scale. The low-rise subarea of Geylang has a denser drainage network compared to the high-rise one. This difference in the drainage system between the two categories is shown to be significant in other areas of Singapore. While an extensive drainage network reduces the risks of flooding, this hydraulic system could increase dengue breeding habitats. In Singapore, the drainage system of rainwater is separate from the sewer system of wastewater. Thus, urban catchments and subcatchments have extensive drainage network in neighborhoods. This system includes more than 7,000 km of drains in areas that convey the rainwater to 32 rivers. The storm water is then directed to 17 reservoirs before being treated and pumped back into the water supply network (Khoo, 2009). Any defection or clogging along this extensive network of drains could result in water stagnation, which can turn into a breeding habitat for mosquitoes. Infestation of perimeter drains from domestic containers, and vice versa, can maintain the vector population against the vector control. This interaction between indoor and outdoor breeding could be one of the reasons for the higher house index in the low-rise households. Further research is needed to reveal whether indoor and outdoor breeds of *Ae. aegypti* in low-rise housing are different or same populations.

A limitation of this study is a lack of spatially explicit data on the human population structure in Geylang. We tried to overcome this limitation by conducting a sensitivity analysis assuming that the nonresident population in the low-rise is twice that in high-rise areas. If this is true, then more cases are reported in the low-rise houses because herd immunity is lower in this section compared to the high-rise one. According to a recent

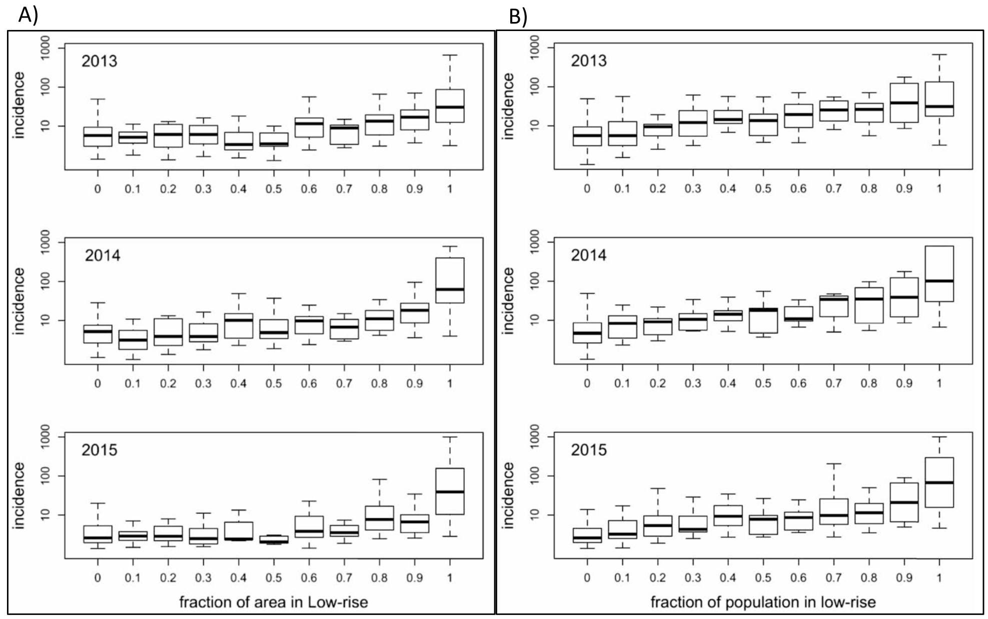

Figure 7. (a) Box plot for a fraction of the area of low-rise housing versus dengue incidence in Singapore (2013–2015); (b) box plot for a fraction of the population living in low-rise housing versus dengue incidence in Singapore (2013–2015).

study, people living in old residential areas have higher seroprevalence (76.5% versus 63.5) compared to new residential areas in Singapore (Yap et al., 2013).

While adults of *Ae. albopictus* were captured more than *Ae. aegypti* in Geylang neighborhood, specimens of *Ae. aegypti* were trapped mainly in the low-rise subarea. In endemic areas, *Ae. albopictus* shows a less vectorial competence to transmit dengue, especially when *Ae. aegypti* coexists (Gratz, 2004). Nevertheless, results of outdoor gravitraps should be considered as qualitative because of the small number of installed traps. A previous mark-release-recapture study had shown that height of the housing does not affect the dispersal ability of *Ae. aegypti* in Singapore (Liew & Curtis, 2004). However, availability of humans and breeding sites could have an impact on the mosquito dispersal. Here we suggest that the man-vector contact happens close to the breeding habitats whether indoor or outdoor. For example, dengue cases cluster in the low-rise area of Geylang because they are close to breeding drains and mosquito does not need to fly far to get a blood meal.

Previous work has shown that feeding of *Ae. albopictus* on humans is less in rural areas and likely depends on human density in Singapore (Kek et al., 2014). In contrast, the study showed that *Ae. aegypti* is a highly anthropogenic-blood feeder in urban and periurban areas. A lower population density in landed houses may widen the difference in human feeding behavior between *Ae. aegypti and Ae. albopictus* and hence increase the relative importance of *Ae. aegypti* at these areas. In contrast, the large human population of

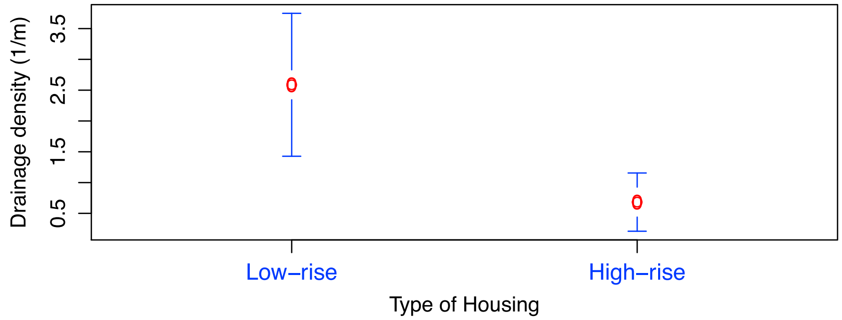

Figure 8. Mean and 95% confidence interval (CI) of the drainage density in low-rise (n = 309) and high-rise (n = 293) residential areas.

HDBs and condos could limit the disease transmission considering the low seroprevalence rate (i.e., mosquitoes feed more on noninfectious individuals). Further work is required to investigate the frequency of human-breeding site contact in low-rise housing in Singapore and how reducing this contact affects the disease transmission. Antivector measures in low-rise housing should focus on interrupting people contact with breeding habitats. These interventions may include the use of spatial repellents (Achee et al., 2012) and personal protection measures, limit people visit positive areas during outbreaks, and enhance a nonconducive environment for outdoor breeding (e.g., periodic cleaning of drains) or barriers for the interaction of indoor-outdoor habitats.

The differences in dengue incidence and abundance of the primary vector between low-rise and high-rise housing suggest that human-breeding site contact—whether indoor or outdoor—influences dengue transmission in Singapore. The short flight range of the dengue vectors can explain the finding that trapped adults of *Ae. aegypti* were also found in low-rise housing, and the primary vector remains close to the breeding sites whether these habitats are outdoor drains or indoor. We suggest describing the risk of dengue transmission in low-rise housing as a function of "human-breeding site contact" instead of "man-vector contact" (which is widely used to consider adult females). The risk of dengue transmission in low-rise housing is likely a result of the interaction of indoor-outdoor breeding habitats in this type of accommodation.

In conclusion, the density of the urban drainage in residential areas of Singapore influences dengue distribution. A redevelopment of low-rise housing areas is needed to improve both indoor and outdoor environments that are conducive to dengue transmission. The density of the drainage networks in endemic cities should be the least required to prevent both storm water flooding and breeding of urban mosquitoes. Public housing plans should also set directions and guidelines for the control of dengue and other vector-borne diseases in human settlements.

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