

# Spatial Components in Disease Modelling

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**Abstract.** Modelling of infectious diseases could help gain further understanding of their diffusion processes that provide knowledge on the detection of epidemics and decision making for future infection control measures. Conventional disease transmission models are inadequate in considering the diverse nature of a society and its location-specific factors. A new approach incorporating stochastic and spatial factors is necessary to better reflect the situation. However, research on risk factors in disease diffusion is limited in numbers. This paper mapped the different phases of spatial diffusion of SARS in Hong Kong to explore the underlying spatial factors that may have interfered and contributed to the transmission patterns of SARS. Results of the current study provide important bases to inform relevant environmental attributes that could potentially improve the spatial modelling of an infectious disease.

**Keywords:** Spatial model, GIS, SARS, Risk factors.

## 1 Introduction

Acute respiratory infections were transmitted through aerosol transmission of respiratory secretions from coughing and sneezing. Conditions such as overcrowding and poor personal hygiene tend to facilitate the transmission of respiratory diseases [1]. Education about personal hygiene and simple intervention measures such as washing hands can help to minimize disease incidence [2][3][4]. A model of SARS transmission by Riley *et al.* [5] suggested that the spread of SARS is highly geographical and localized such that a complete ban on travel between local districts could expect to reduce the transmission rate by 76%. Therefore, a closer examination of the SARS occurrences in space and time could provide a better understanding of the spatial diffusion patterns and possible environmental factors contributing to such patterns. Besides, an enhanced understanding of the spatial spread could extend knowledge on the detection of epidemics and help advice infection control and intervention measures. It is also known that conventional disease transmission models are inadequate in considering the diverse nature of a society and its location-specific factors [6][7][8]. This research made an attempt to map different phases of the spatial diffusion of SARS in Hong Kong to identify the underlying spatial factors attributing to

its transmission patterns. Results from the study offer useful guidance about the selection of environmental risk factors for inclusion in the spatial modelling of an infectious disease.

## 2 “Space” as an Element in Disease Modelling

Various efforts have been made to simulate the outbreaks of SARS using mathematical methods [5][9][10][11][12]. Many of the models were based on the deterministic approach, such as SEIR, which incorporates the susceptible population (S), exposed/infected population (E), infectious population (I), and the recovered (immune) / removed (death) population (R) [5][10][12]. SEIR models explain the diffusion of a disease among the four population groups.

SEIR and other related models often require little data, are relatively easy to set up, and can generally simulate infectious disease dynamics among the population [13]. Such models, however, do not consider dynamic elements transpired by population mobility and social mixing; both of which are largely influenced by socio-economic and environmental factors. Small and Tse [14] explained that these conventional models have an underlying assumption that each member of the entire population has an equal chance of being infected. Such an assumption ignores the complex socio-demographic and environmental factors afflicting the transmission course of a disease among various subgroups (e.g., the wealthy, middle class, and the disadvantaged). A typical mathematical model suggests that a disease epidemic would ultimately infect the entire population [10][12]. The reality is that certain communities may be affected less by an epidemic. For example, SARS cases seemed to cluster in several disease “hot spots” in Hong Kong [15]. Jefferson *et al.* [16] also reported that simple physical interruptions, such as systematic education on personal hygiene and isolation of infected patients, were effective in preventing the spread of respiratory diseases. Hence, Dye and Gay [9] concluded that the next generation of disease models should include spatial processes and stochastic factors to tender a better solution to the problem.

The Geographic Information System (GIS) technology is well suited for analysing epidemiological data and characterising the spatio-temporal patterns of epidemics [15][17]. Epidemiological data often have a spatial context, such as the residential or work addresses of patients and the spatial patterns associated with a disease. Efforts have been made to incorporate the dimension of space into disease simulation. Sattenspiel and Dietz [7], for example, created an epidemic model that accounts for geographic mobility of the population in different regions. Despite the assumptions of a single trip and a static population, their model was regarded superior to the conventional SEIR models because it considered in calculating the transmission risk both epidemic and behavioural processes, as well as environmental factors. Small and Tse [8] modelled the spread of SARS using a small

world model to simulate its spatial diffusion using the network structure. However, their model assumed that the environmental factors and population composition within the small world were homogenous. Meng *et al.* [18] tried to employ spatial analysis to investigate and understand factors affecting the spatial transmission process of SARS in Beijing. They identified population density as a significant factor for the spatial diffusion in this case. However, “population density” alone may not reveal overcrowding conditions at the micro-level, especially in places like Hong Kong where a mixed land use is not uncommon and where non populated country parks are adjacent to urbanized areas.

Riley [17] documented four kinds of models (patch, distance, group and network) for the transmission of infectious diseases. He applied these models to simulate various disease outbreaks in the UK and found the group model to be the most suitable for human-to-human transmission of influenza. Watkins *et al.* [19] also tried to model infectious disease outbreaks using a GIS to incorporate traditional SEIR models in their simulations. Their examples also showed that the establishment of a spatial model for contagious diseases (such as SARS) was essential in understanding how the disease spread through time and space. Furthermore, Hsieh *et al.* [20] highlighted the importance of creating distinct and explicit spatial models for the understanding of the specific patterns of transmission of SARS in each region or country.

A new approach seems necessary to address the location-specific as well as environmental and socio-demographic risk factors for communicable diseases. However, only a limited number of studies (such as Lau *et al.* [3]) has identified some risk factors for the SARS transmission in Hong Kong. This study is an attempt to isolate risk (or stochastic) factors to model the transmission dynamics of a disease in space. The study is based on data collected for the 2003 SARS outbreak of Hong Kong.

### 3 Research Method

Our approach attempts to extract features in space that contribute towards social mixing. We argue that social mixing is a function of transport infrastructures and can also be reflected through certain social-economic indicators.

#### 3.1 Study Area and Data Period

The study area covers the whole territory of Hong Kong and the data include 1,707 confirmed cases of SARS occurring between February and June 2003. We divided the SARS epidemic into four phases and by spatial units of 18 districts to explore its spread across space and time.

- 1) Early phase, with cases admitted on or before March 10, 2003 (when patients in room 8A of the Prince of Wales Hospital were isolated);
- 2) Diffusion phase, with cases admitted between March 11 and March 17 inclusive

- 3) SSE phase, with cases admitted between March 18 (when the Super Spreading Event or SSE at the Amoy Garden was estimated to begin according to Riley *et al.* [5]) and March 30 inclusive;
- 4) Post-SSE phase, with cases admitted between March 31 (when Amoy Garden residents were segregated) and June 2 (last case admitted and end of the 2003 SARS epidemic of Hong Kong).

### 3.2 Research Hypotheses

Our research hypotheses are as follows:

- 1)  $H_0$ : There is no relationship between disease spread and transport infrastructure  
 $H_A$ : Disease spread follows the pattern of transport infrastructure
- 2)  $H_0$ : There is no relationship between disease incidence and various socio-economic characteristics (refer to section 3.3 for such characteristics)  
 $H_A$ : Disease incidence correlates with various socio-economic characteristics

### 3.3 Data Processing

We obtained the SARS data from the Hong Kong Hospital Authority. A patient record includes an identifier, residential address, hospital admission date, onset date of symptoms, hospital admitted to, as well as health conditions at admission. Personal particulars of individuals were stripped and their residential addresses were replaced with geo-coordinates, with no information about flat numbers and building names, to ensure data privacy.

We employed the 2004 geographical data (B5000 for the whole of Hong Kong) acquired from the Lands Department the Hong Kong Special Administrative Region (HKSAR) government for spatial analysis and spatial modelling of SARS. The ArcGIS 9.0 geographic information system software was used as a platform for data input and manipulation. Maps were created to reveal the locations of SARS cases. Aggregation of cases to the 18 districts level was also made to extract potentially risky districts during various phases of the SARS epidemic in 2003.

Demographic and census data of the general population were abstracted from the 2001 Population Census (in street block or small tertiary planning unit levels (STPU)) compiled by the Census and Statistics Department of the HKSAR government [21]. We incorporated such data to investigate possible socio-economic factors that might have affected the spatial distribution of SARS. As the human-to-human transmission of SARS is through close contacts, variations in the socio-economic constructs by different spatial units might influence its spatial distributional patterns [4]. Grids of 150m x 150m were created. SARS data and census data were spatially joined to the grid level for analysis. We examined the relationship between the SARS incidence and the following socio-economic characteristics as stipulated in hypothesis 2 above.

- a) percentage of population with tertiary level education
- b) percentage of population aged under 15
- c) percentage of population aged over 65

- d) non-working population
- e) median household income
- f) median personal income
- g) average number of rooms per household
- h) net residential density

We followed the Irish government's guidelines [22] when defining net residential density because there is no such guideline in Hong Kong. Non populated areas (such as country parks) were excluded in our analysis. The reason for not using population density directly is because many areas in Hong Kong are of the mixed land use type (e.g. inner city areas of Kowloon and northern Hong Kong Island where residential areas are mixed with commercial / retail uses). Moreover, some residential areas are also situated adjacent large plots of non populated country parks (please refer to Figure 3 for such situations in Kowloon and the Hong Kong Island) which are often included in the total area of specific administrative districts or planning units. Population density in these areas will therefore be under-represented and not reflecting truly how crowded a place is.

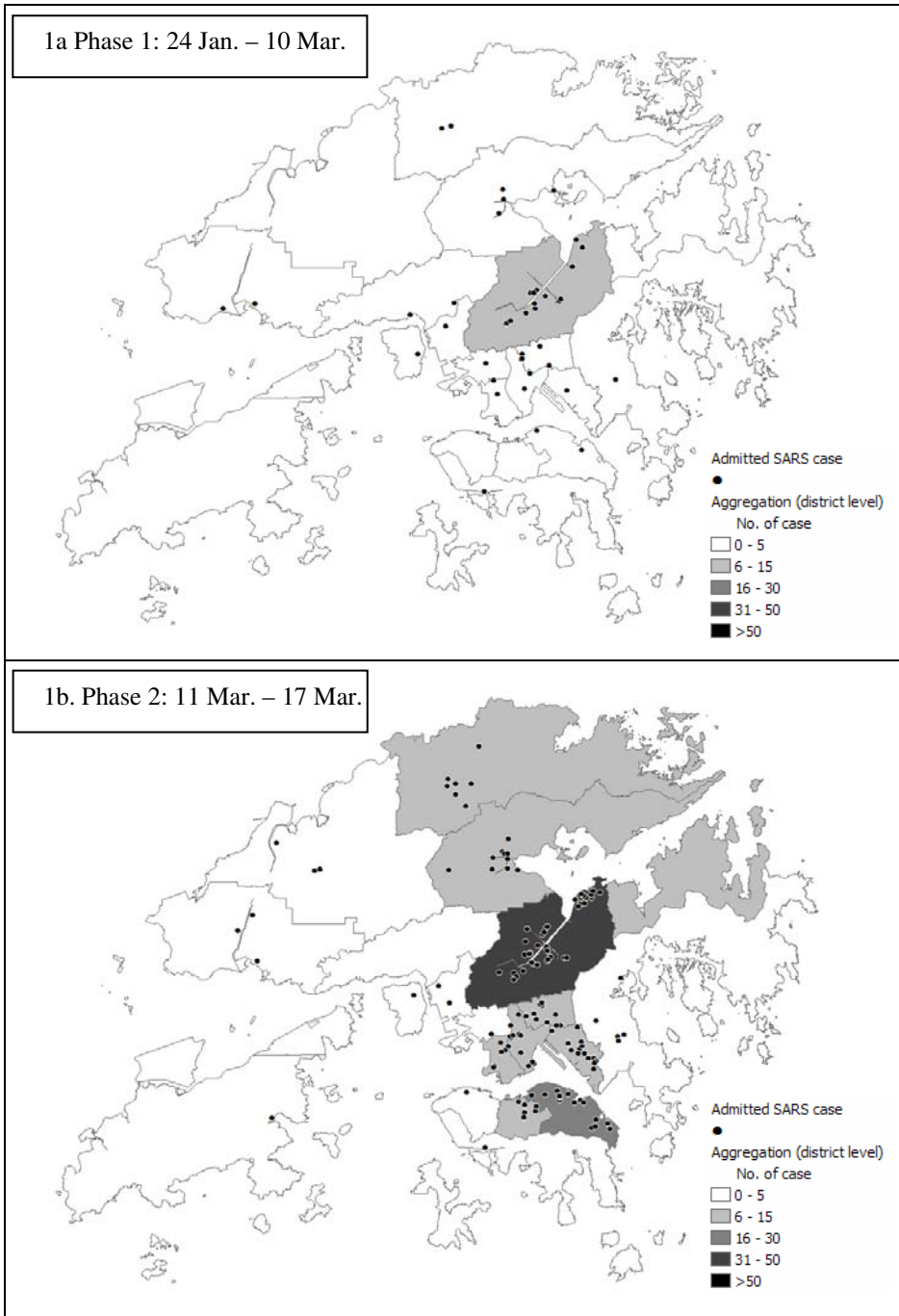
Statistical methods, including Pearson's correlation co-efficient, were employed to determine the significance of various environmental and demographic factors contributing to the spatio-temporal transmission of SARS.

## 4 Results and Discussion

### 4.1 Spatio-Temporal Diffusion of SARS

Figure 1 maps the four phases of the 2003 SARS epidemic outbreak in Hong Kong. It seems that disease cases were concentrated in the Sha Tin district in the first phase or the early stage (Figure 1a) before spreading to the North and South in phase 2 or the diffusion stage (Figure 1b). A concentration of SARS cases remained apparent in both Sha Tin (13.6% of 1515 cases) and Kwun Tong (34.2% of 1515 cases) districts in phases 3 and 4 (Figures 1c and 1d) when SARS became widespread throughout the whole territory of Hong Kong.

An interesting point to note is that the north-south linear spread pattern in the early stages of the epidemic, as illustrated in Figures 1a and 1b, corresponds to the East Rail line which is a heavily used mass transit railway connecting Kowloon and the Northeast New Territories (Figure 2). It appears that transport might have an essential role in facilitating disease spread. A previous study of SARS transmission in China also confirmed that modern public transport has a vital part in spreading contagious diseases like SARS [23]. The study reported that SARS had two major hotspots in Guangdong and provinces near Beijing. Intersections of national highway, in particular, were a high risk factor for the spatial diffusion of SARS. While an appropriate test of significance is not available, the visual evidence derived of the SARS data in our study does suggest that the null hypothesis 1 is not substantiated.



**Fig. 1.** Diffusion patterns in four phases of the SARS epidemic in 2003

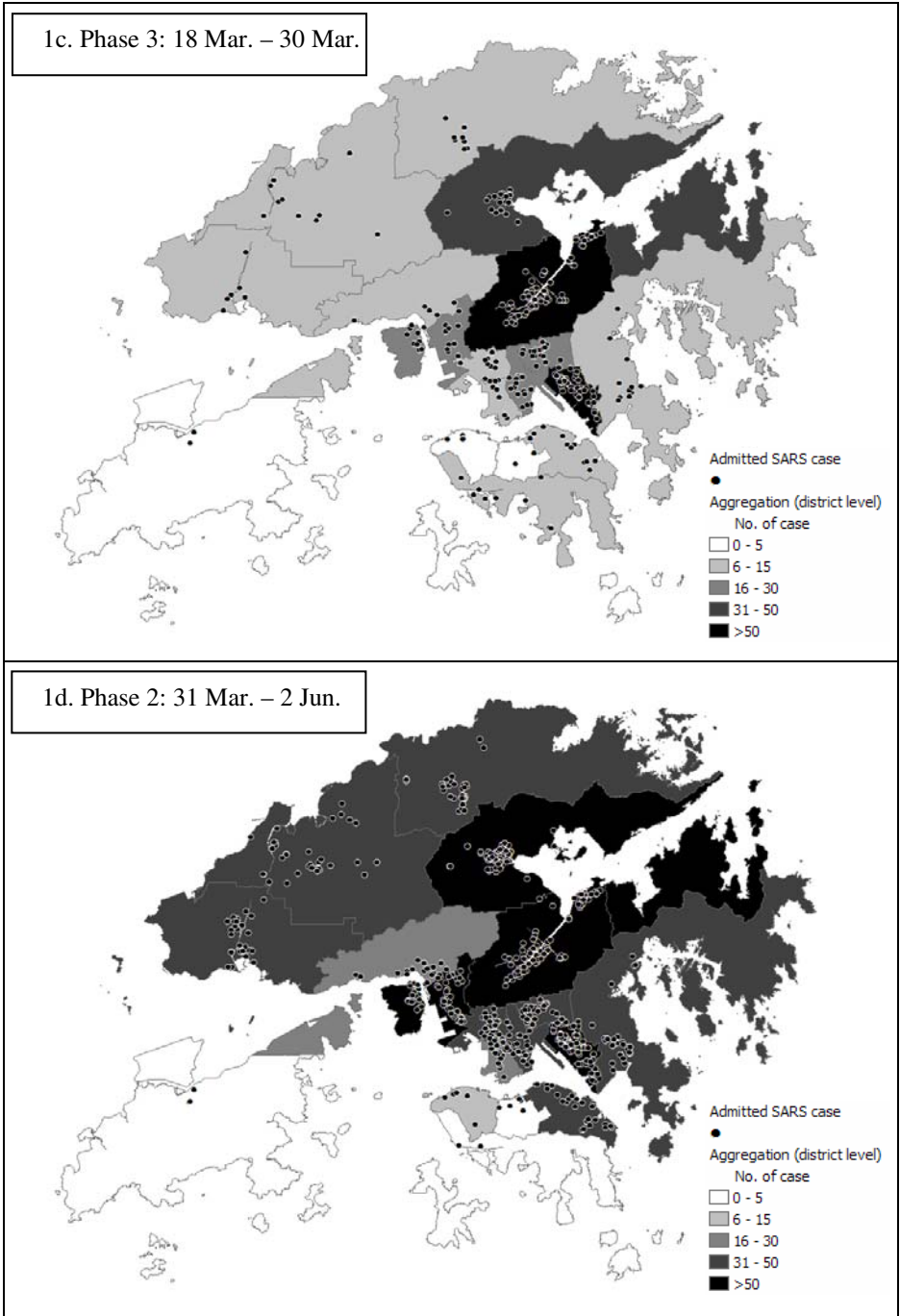
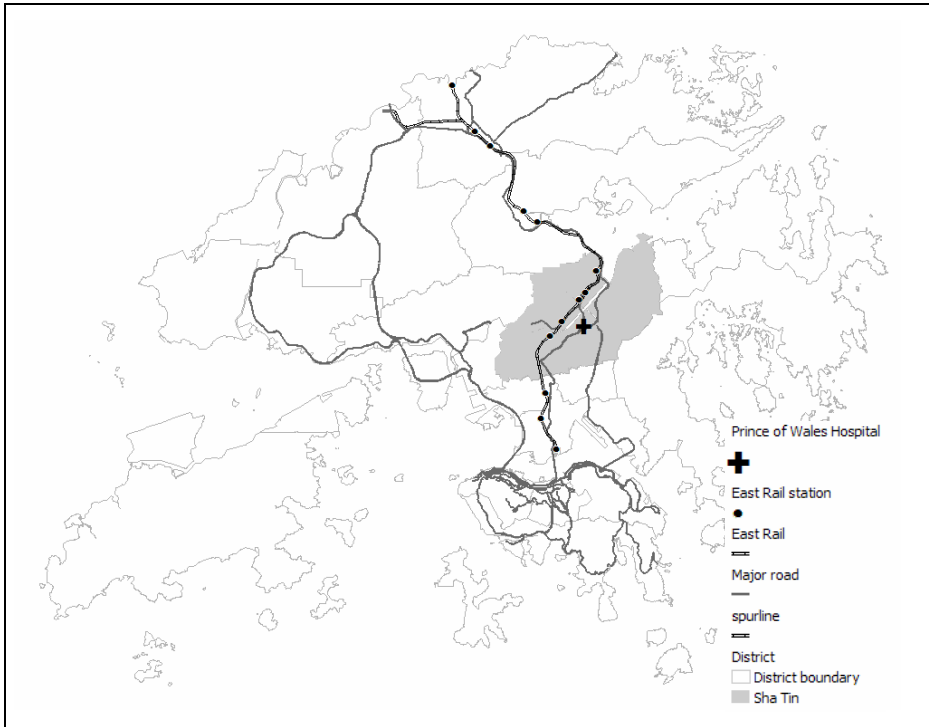


Fig. 1. (continued)



**Fig. 2.** Major transport infrastructures of Hong Kong

Medical facilities could be another important contributor to the diffusion of SARS. More than 10 workers in room 8A of the Prince of Wales Hospital (PWH), where the first SARS patient was admitted, were infected with SARS in early March [24]. Figure 1 shows that the Sha Tin district, where the PWH is located, was most severely affected by SARS during the first two phases of the epidemic in 2003. Confirmed cases in Sha Tin for phases 1 and 2 accounted for 34.9% (15 out of 43) and 28.2% (42 out of 149) of total SARS cases in Hong Kong. The close proximity of residents in Sha Tin to the PWH, which is the primary source of nosocomial infection, meant that they were at a higher risk of contracting SARS in the early phases of the epidemic. This is in line with Lau *et al.* [2][3] who suggested that more than a quarter of the SARS patients in Hong Kong in 2003 were health care workers and hospital visit was a risk factor for contracting SARS. Similar conclusions were made by Meng *et al.* [18] that medical care resources affected the spatial contagion of SARS in Beijing.

#### 4.2 Socio-economic Factors Related to the SARS Epidemic

Socio-economic factors found statistically significant against SARS incidence included the following: c) percentage of population aged over 65, g) average number of



**Table 1.** Pearson's Correlation Co-efficiency results between socio-economic factors and occurrence of SARS, SARS cases in a grid (150m x 150m) as the dependent variable

Variables	Co-efficiency	Sig.	N
<b>Grids with SARS cases only</b>			
c) % of the population over 65 years old	.062 (*)	.025	1316
g) Average no. of rooms per household	-.098 (**)	.000	1316
h) Net residential density	.204 (**)	.000	1316
<b>All grids (excluding country parks)</b>			
c) % of the population over 65 years old	-.020 (**)	.001	28303
g) Average no. of rooms per household	-.098 (**)	.000	28303
h) Net residential density	.390 (**)	.000	28303

\*\* Correlation is significant at the 0.01 level (2 tailed).

\* Correlation is significant at the 0.05 level (2 tailed).

rooms per household, and h) net residential density (Table 1). All other variables did not exhibit a statistically significant relationship with the occurrence of SARS. Table 1 also shows that net residential density had a significant positive correlation with the occurrence of SARS.

Figure 3 is a map of SARS cases plotted over residential density in the city centres of Hong Kong (Kowloon and the Hong Kong Island). It illustrates that disease cases were concentrated mostly in areas of high residential densities. Areas with lower residential densities in Figure 3 (such as 1 - Kowloon Tong, 2 - Southern District, and 3 - mid-levels) had fewer cases throughout the 2003 epidemic as shown in Figure 1. This observation matches that of a study by Meng *et al.* [18] who demonstrated that population density was an important factor affecting the spatial diffusion of SARS in Beijing. The average number of rooms per household was also found to have a statistically significant negative correlation with SARS because this factor is likely associated with residential density. People must share a room with their family members given fewer rooms per household in places with a high residential density. The percent of elderly population (over 65 years old) was statistically significant at the less stringent 95% instead of 99% confidence level. While the elderly have been found more susceptible to various types of infectious diseases including SARS [25][26][27], their less active social role could have ameliorated the chance of contracting a contagious disease.

The results indicate that the null hypothesis 2 can be rejected for socio-economic characteristics of net residential density, average number of rooms per household, and elderly population. In other words, these three characteristics exhibited statistically significant correlation with the occurrence of SARS in Hong Kong. These socio-economic factors could be used to explain the transmission patterns of the 2003 SARS epidemic.

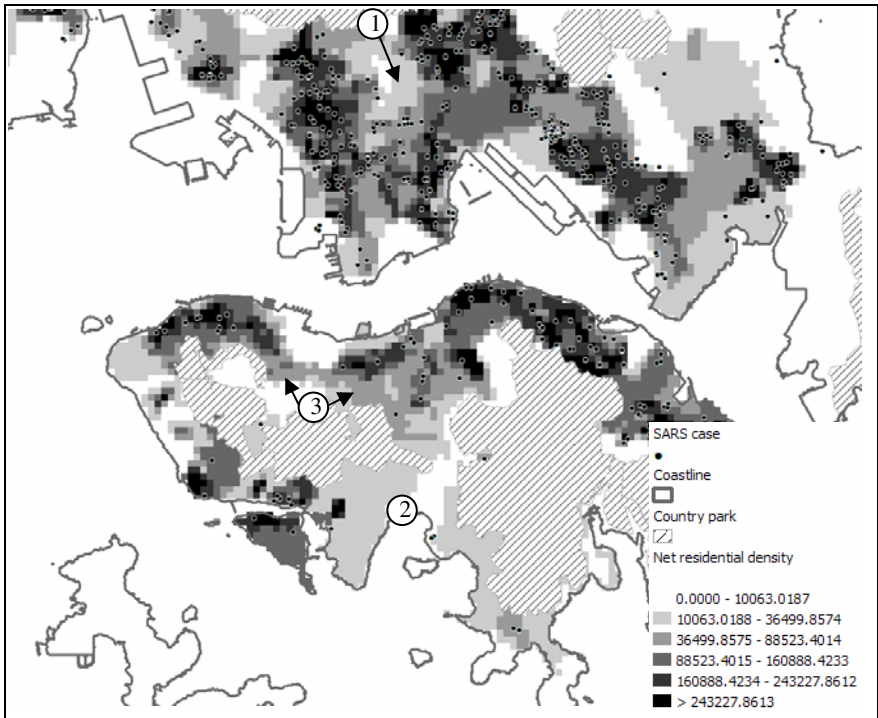


Fig. 3. Residential density and SARS cases (Kowloon and Hong Kong Island)

## 5 Conclusion

New and re-emerging of infectious diseases post challenges and threats to the health systems of many countries. While medical treatment of patients with contagious diseases has been top priority in curtailing epidemics, surveillance and early warning are equally important [1]. Deterministic and mathematical models of communicable diseases are not adequate as a decision tool because they fall short of providing information about an epidemic form the spatial perspective. Moreover, these models are not able to account for stochastic factors that influence the spatial dispersion of a disease outbreak. Previous studies of the diffusion of SARS in Hong Kong and Beijing have shown evidence of geographical concentrations of SARS cases [15][18]. Further efforts to incorporate stochastic events in modelling the spatio-temporal transmission of an infectious disease such as SARS are therefore necessary.

GIS provides an integrated platform for the examination of spatio-temporal diffusion of a disease. This research studies SARS diffusion in space and various temporal phases of the 2003 epidemic using the GIS technology. We have identified some environmental and demographic factors deemed important in affecting the spatial transmission of SARS. Obtaining results that are in line with similar studies in other places, our study concluded that environmental factors (in this case, transport infrastructure and hospital locations) played a key role in shaping the diffusion pattern of

SARS. Certain socio-economic factors (i.e., average number of rooms per household, percentage of elderly population, and net residential density) were found to correlate positively with the occurrence of SARS in Hong Kong, indicating their potential influence in the disease transmission.

The research findings set the groundwork for the construction of a combination of stochastic and geographical-based models to simulate the transmission patterns of an infectious disease in space and time. Previous studies have documented deficiencies of deterministic models in addressing spatial differences and severity of an epidemic. This research mapped different development phases of the SARS epidemic in Hong Kong and employed the Pearson's correlation to isolate environmental factors and socio-economic factors of significant pertinence to the disease. The results are useful in paving the ways forward to study disease transmission in space and time. Future studies may take heed of our research findings to construct spatial models of disease transmission. The risk factors identified in this study could be incorporated in the modelling process to improve model predictability.

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