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GIS-based surface roughness evaluation in the urban planning system to improve the wind environment – A study in Wuhan, China

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ABSTRACT

Due to the rapid urbanisation, the urban environment has been changed and deteriorated. One of reasons is lack of consideration and implementation of climatic and environmental information in urban planning. Thus, there is a need to develop a systematic method for city planners and policy-makers to make scientific and evidence-based decisions in the urban climatic and environmental field. Taking Wuhan as an example, this study aims to provide a practical framework to identify planning goals and guidelines for master and district planning, based on the results of roughness modelling. Both meteorological information and 3D urban morphology data were simplified and integrated in a Geographical Information System (GIS) to provide the detailed information of the urban permeability distribution. Based on this spatial distribution information, both master and district planning goals for better urban wind environment can be particularly identified and corresponding planning strategies can be established. With this spatial urban permeability information and the joint effort from local town plans and policy-makers of the Planning Bureau of Government, urban planning strategies for different spatial scales and districts can well corporate with each other and be interwoven into the whole urban planning process.

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1. Background

In the last 20 years, major cities in China have undergone rapid urbanisation. Wu Han, with an area of some 8500 km^2 and a population of over 10 million, is located inland and west of Shanghai. It is one of the mega cities in China and is the country's high speed rail hub. In the summer months, Wu Han is hot; the average daytime temperature of the city is around 33 degrees Celsius. The city planners of Wu Han have been postulating the idea of urban air paths for a number of years for the making of their master plan. This study to better identify and quantify the wind path idea was commissioned by the City Planning Bureau of the Wu Han City Government in 2012. The study intended to provide evidence based knowledge for Wu Han's planners.

2. Literature review

The public concern on good quality of living environment has kept on rise in the world. German and Japan lead pioneering work in the field of urban climatic application into the urban planning (Ren et al., 2011). German cities have protected their urban environment carefully in the local development since the 1950s. Stuttgart Municipal Government pays its continuing effort to upgrade the air quality of Stuttgart. One of their useful measures is the air path development (Baumueller et al., 2009). In this plan, scientists, urban planners and local governors work together to evaluate the air-flow distribution patterns, to detect the possible air paths which can bring the fresh air from the surrounding hillsides to the downtown areas of Stuttgart, and to control the urban development carefully and strategically. The relevant plan actions have played an important role on mitigating urban heat island and improving air quality.

Japan researchers and government has paid their high attention on the wind environment since the 1990s. Tokyo Metropolitan Government including eight main counties finished a study on air path in 2007. In the report, it collected the relevant wind information for planners, like wind rose information, annual and seasonal prevailing wind information, land-sea breezes system, and also provided the detailed plan of developing air paths in Tokyo Metropolitan areas (Architectural Institute of Japan, 2008).

Hong Kong is one of most high-dense and populated city in the world. Natural ventilation in urban planning is a big challenge to local planners and governors. Recently "Wall-buildings" have been constructed. They highly affect local air circulation. Thus, local researchers and governors has worked together to develop a wind information layer for planning use based on the available meteorological records, CFD simulations and expert evaluation(Ng, 2012). This layer has been used by the Planning Department of Hong Kong Government to guide the new town plan and urban renewal.

3. Objectives

The study of outdoor natural ventilation often requires large-scale aerodynamics modelling. Both physical modelling (wind tunnel) and numerical modelling can provide data regarding the airflow within the urban canopy layer. However, conducting these modelling tests for a particular urban planning exercise is expensive and time consuming. Modelling results cannot keep up with the quick planning processes, as such, Ng et al. (2011) opines that a methodology that uses a rougher understanding of the urban morphological implication to the urban wind environment can be more useful to planners. Given the growing concerns related to the way urban environment is evaluated and air paths are detected in order to fit the requirements of practical urban planning, this study aims to:

- introduce the morphological method to model urban surface roughness and evaluate urban permeability;
- analyse urban permeability to detect potential air paths to improve urban performance in outdoor natural ventilation;
- highlight the implementation of modelling results in urban planning practices and interweave the modelling results into different urban planning stages and scales, such as the master and district planning.

This study focuses on Wuhan described at background as an example. By applying the morphological modelling method with Wuhan's local GIS data (3D building database), the planners can easily evaluate the urban permeability to understand the outdoor natural ventilation performance of the city for evidence-based decision making in urban planning.

4. Study approach

4.1. Morphometric method

The morphometric method of surface roughness modelling (Grimmond and Oke, 1999; Lettau, 1969; MacDonald et al., 1998) is widely used to estimate the wind profiles in the urban boundary layer (UBL), as shown in Fig. 1. Based on a 3D building database and current modelling method, Gál and Unger (2009) visualised and mapped the roughness length (Z_0) in pixels at urban areas to diagnose the urban wind environment. To make the evaluation of urban permeability more practical for and available to urban planners, urban geometric parameters, such as frontal area density (λ_f) and site coverage ratio (λ_p) which were used to estimate both surface roughness length (Z_0) and zero-plane displacement height (Z_d) (Grimmond and Oke, 1999), were directly used to evaluate the urban permeability (Ng et al., 2011; Wong et al., 2010).

The basic assumption in the current morphological models, such as the models provided by MacDonald et al. (1998), Lettau (1969), and Bottema (1996), was stated by MacDonald et al. (1998) as: '…*we assume that there is negligible wake interference between the surface obstacles and that the mean velocity profile approaching each obstacle is logarithmic.* '. Due to this assumption, the reason why these models are only valid when frontal area density (λ_f) is less than about 0.3–0.5 could be obvious; that is, with the roughness increasing, the mean velocity profile approaching each obstacle is not logarithmic because the interference among obstacles promotes the recirculating flow which dominate the flow near the ground.

It is why the displacement height (d) needs to be introduced into the logarithmic velocity profile (MacDonald et al., 1998). Above the displacement height, the mean wind profile approaching the obstacle become to be logarithmic again as shown in Fig. 1. Therefore, MacDonald et al. (1998) pointed out that frontal area density above the displacement height (λ_f^*) could be better to estimate Z_0 than λ_f, and developed the in-canopy logarithmic profile and the mean wind speed below the displacement height (a new smooth surface) was assumed to be zero in the derivation. The above analysis brings a great trouble to the practical application of the near ground wind speed estimation at high density urban areas. A lot of reliable wind tunnel experiments have proof that the wind speed below the displacement is not zero at the high density areas. Rather than the logarithmic profile model developed by MacDonald et al. (1998), exponential solution was introduced by Cionco (1965) and Coceal and Belcher (2004) developed the in-canopy model by parameterising the canopy element drag

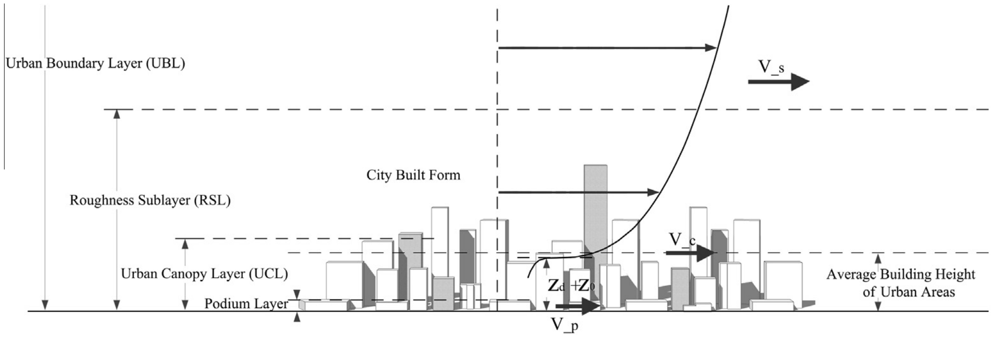

Fig. 1. Wind speed profile, podium layer, building layer, urban canopy layer, and roughness sublayer (RSL). V_p, pedestrian-level wind speed; V_s, the wind speed at the top of roughness sublayer (Ng et al., 2011).

($D_i(x,y,z)$) and turbulent mixing $\langle \overline{u_i' u_j'} \rangle$. But as Coceal and Belcher (2004) mentioned, a balance between sectional drag and shear stress is assumed in the exponential models, and the model for the spatially averaged mixing length (l_m) may fails when recirculating flow dominate the flow near the ground with very densely packed canopy element. We shall find in Section 4.4 that λ_f in this study could be larger than 1.0 at metropolitan areas.

Therefore, the spatially averaged wind speed below the displacement height could depend on the building geometries such as λ_f' (frontal area density below the displacement height) in high density areas, instead of λ_f^* by which the mean wind profile above the displacement height can be well identified. The cross-comparison conducted by Ng et al. (2011) supported the above hypothesis; that is, the VR (the ratio of pedestrian-level wind speed to the wind speed at the reference height) is well related with $\lambda_f'(\lambda_{f(0-15\mathrm{m})})$, rather than λ_f^* ($\lambda_{f(15-60\mathrm{m})}$) and $\lambda_{f(0-60\mathrm{m})}$. In particular, frontal area density ($\lambda_{f(z,\theta)}$) at a height increment of 'z' is calculated as (Burian et al., 2002):

$$\lambda_{f(z,\theta)} = \frac{A(\theta)_{proj(z)}}{A_T} \tag{1}$$

where $A(\theta)_{proj(z)}$ is the frontal area facing the incoming wind direction θ in the height band 'z', and A_T is the site area. In contrast to the frontal area index ($\lambda_{f(\theta)}$), which is an average parameter for the entire urban canyon layer, $\lambda_{f(z,\theta)}$focuses on the urban morphology at the height band 'z'.

To evaluate urban permeability based on the annual outdoor natural ventilation performance, $\lambda_{f(z,\theta)}$ calculated at different prevailing wind directions were averaged based on the respective annual wind probabilities ($P_{\theta i}$):

$$\lambda_{f(z)} = \sum_{1}^{i} \lambda_{f(z,\theta)} \cdot P_{\theta,i} \tag{2}$$

where $\lambda_{f(z)}$ is the annually averaged $\lambda_{f(z,\theta)}$, and $P_{\theta,i}$ is the annual wind probability in the ith wind direction θ. By using a high-resolution (1 m × 1 m) building height database, a self-developed program embedded as a VBA script in the ArcGIS system is applied to calculate the frontal area density $\lambda_{f(z)}$ in Eq. (2).

4.2. Validation

The wind tunnel data from the Hong Kong University of Science & Technology (Hong Kong Planning Department, 2008), i.e. the wind velocity ratio ($VR_{w,j}$: the ratio of wind velocity at the pedestrian-level to that at the reference height of 500 m) was used to test the sensitivities of the site's permeability across the different $\lambda_{f(z)}$ which were calculated at three height bands 'z': the podium layer, building layer, and canopy layer (Fig. 1).

The cross-comparative results were plotted in Fig. 2. The R^2 values indicate that the pedestrian-level site permeability mostly depends on $\lambda_{f(z)}$ at the podium layer ($R^2 = 0.87$), and is related with $\lambda_{f(z)}$ at the canyon layer ($R^2 = 0.60$). This indicates that the airflow above the urban canyon may not easily vertically enter into deep street gaps because of the high density and tall buildings in metropolitan urban areas, and that the pedestrian-level wind environment mostly depends on the horizontal momentum flux in the podium layer (Ng et al., 2011).

4.3. Classification

Based on the linear relationship reported by Ng et al. (2011), as shown in Fig. 3, the values of $\lambda_{f(z)}$ were classified as follows: (1) $\lambda_{f(z)} \leq 0.35$; (2) $0.35 < \lambda_{f(z)} \leq 0.45$; (3) $0.45 < \lambda_{f(z)} \leq 0.6$; and (4) $\lambda_{f(z)} > 0.6$. This classification aims to statistically weigh the effects of different values of $\lambda_{f(z)}$ on the pedestrian-level natural ventilation performance, and to detect the potential air paths (the areas with low surface roughness) in high-density urban areas. For instance, Class 4 ($\lambda_{f(z)} > 0.6$) indicates that the wind velocity ratio ($VR_{w,j}$) maybe less than 0.1, which implies very poor natural ventilation. In contrast, Class 1 ($\lambda_{f(z)} \leq 0.35$) indicates that VR_wj may be larger than 0.2, which implies good natural ventilation (Ng et al., 2011).

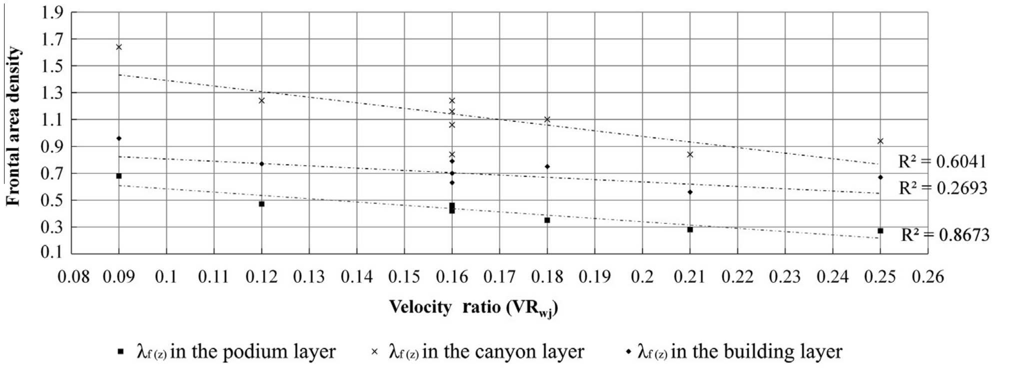

Fig. 2. Relationships between $VR_{w,j}$ and $\lambda_{f(z)}$ as calculated at the podium, building, and canopy layers (Ng et al., 2011).

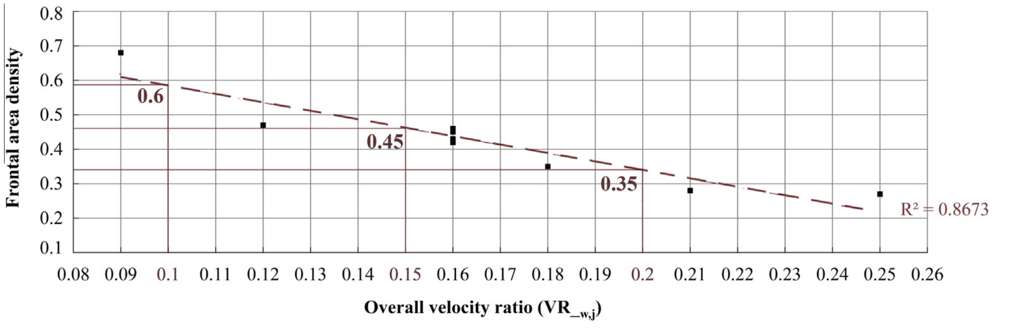

Fig. 3. Linear relationship between $\lambda_{f(z)}$ and $VR_{w,j}$ (Ng et al., 2011). The values of $\lambda_{f(z)}$ were classified as: (1) $\lambda_{f(z)} \leq 0.35$; (2) $0.35 < \lambda_{f(z)} \leq 0.45$; $0.45 < \lambda_{f(z)} \leq 0.6$; and (4) $\lambda_{f(z)} > 0.6$.

4.4. Modelling settings and result in Wuhan

To identify the value of '*z*' in Eq. (1), particularly in the context of Wuhan, this case study calculated the dividing level (27 m) of the building height distribution (0–204 m) using the local 3D building database in GIS. Building height data were analysed in ArcGIS to identify the natural breakpoint (26.65 m), which classified the buildings at metropolitan area into the normal buildings (0–27 m) and high rise buildings (27–204 m). As shown in Fig. 4, the percentage of the normal building class is significantly larger than the one of the high rise building class. Consequently, the urban morphology density at the layer ranging from 0 to 27 m is considered as being much higher than at the layer ranging from 27 to 204 m. Therefore, the value of '*z*' in this case study for Wuhan is set to 27 m.

To identify the local annual prevailing wind probability P_θ of Wuhan in Eq. (2), the wind frequency data from Wuhan Observatory was used. The prevailing wind directions were identified as south ($\theta_1 = 90°$), southeast ($\theta_2 = 135°$), and southwest ($\theta_3 = 45°$), and their frequency is generally similar. Therefore, the values of P_θ, i $(i = 1, 2, 3)$ across three prevailing wind directions are simplified as $1/3$.

After calculating $\lambda_{f(z)}$ at a resolution of $100\ \text{m} \times 100\ \text{m}$ and classifying the results based on Fig. 3, the urban permeability of the pedestrian-level natural ventilation in Wuhan is mapped as shown in Fig. 5. Given the uncertainties in the modelling results caused by the linear regression analysis and other assumptions, the modelling results are considered as acceptable for the planning practices in the initial stages of the decision making process.

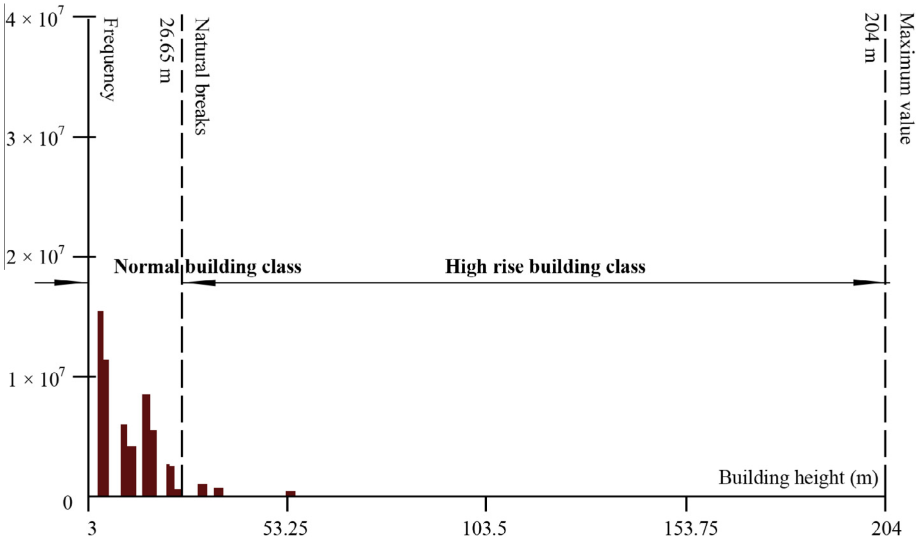

Fig. 4. Distribution of building height at metropolitan area of Wuhan. Natural breakpoint was identified at 26.65 m.

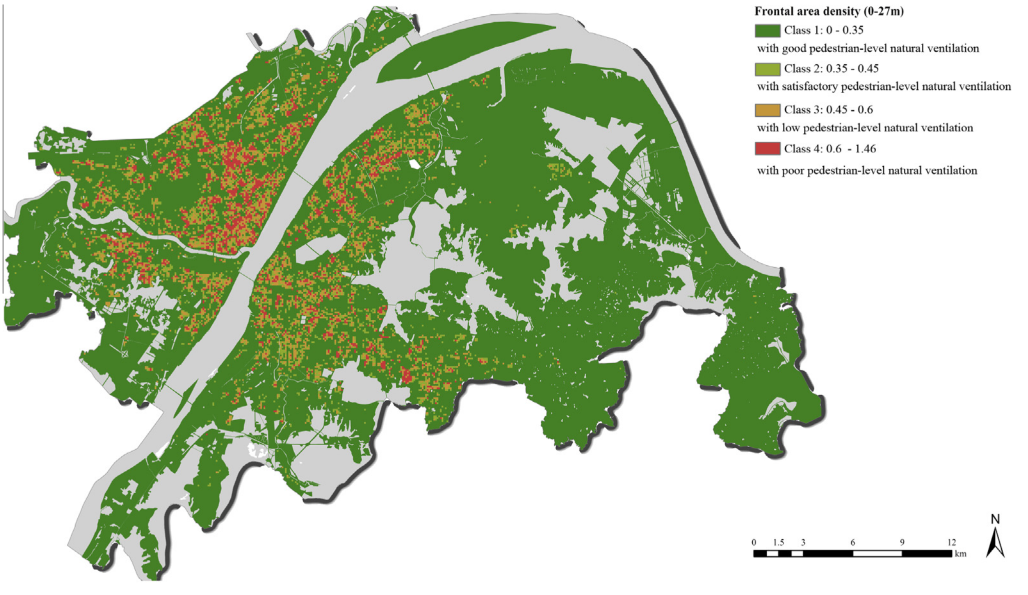

Fig. 5. Urban permeability map of the pedestrian-level natural ventilation in Wuhan.

5. Implementation in urban planning

The urban permeability map shown in Fig. 5 provides urban planners with an intuitive grasp of the natural ventilation of urban areas for the master planning in which the district land use and density are determined. The lower urban permeability areas (Classes 3 and 4) include Hankou, Wuchang, and Hanyang, the downtown areas of Wuhan. It indicates that the airflow in the street canyon is seriously restricted by compact building blocks, and the outdoor natural ventilation may worsen in these areas. By contrast, the surface roughness in the other districts located far from the downtown area is still very low ($\lambda_{f(z)} \leq 0.35$). Compared with these districts in which new development is still acceptable, the urban density at Hankou, Wuchang, and Hanyang should be strictly controlled in the master plan, and particular mitigation strategies in the district planning for these three areas are also necessary.

Based on the above analysis, district-based information is needed to identify the district planning goals and mitigation strategies. The high-resolution urban permeability maps were shown in Fig. 6a and b. The areas with low urban permeability occupy most of Hankou. Compared with Hanyang and Wuchang, the urban permeability in Hankou is relatively low, and in Hankou, the areas with low urban permeability are wide and close to each other, whereas in Wuchang and Hanyang, they are smaller and more scattered. Correspondingly, different district planning goals and mitigation strategies were suggested in the respective districts.

1) Planning goals and mitigation strategies for Hankou

The planning goal for Hankou district is to identify the key areas to make the potential air paths play a role in encouraging the fresh air flow into the deeper urban areas of the city. This strategy is more practicable than decreasing the urban density of the whole district because of the presence of wide urban areas with low permeability. According to the planning goal, the corresponding planning strategies are as follow:

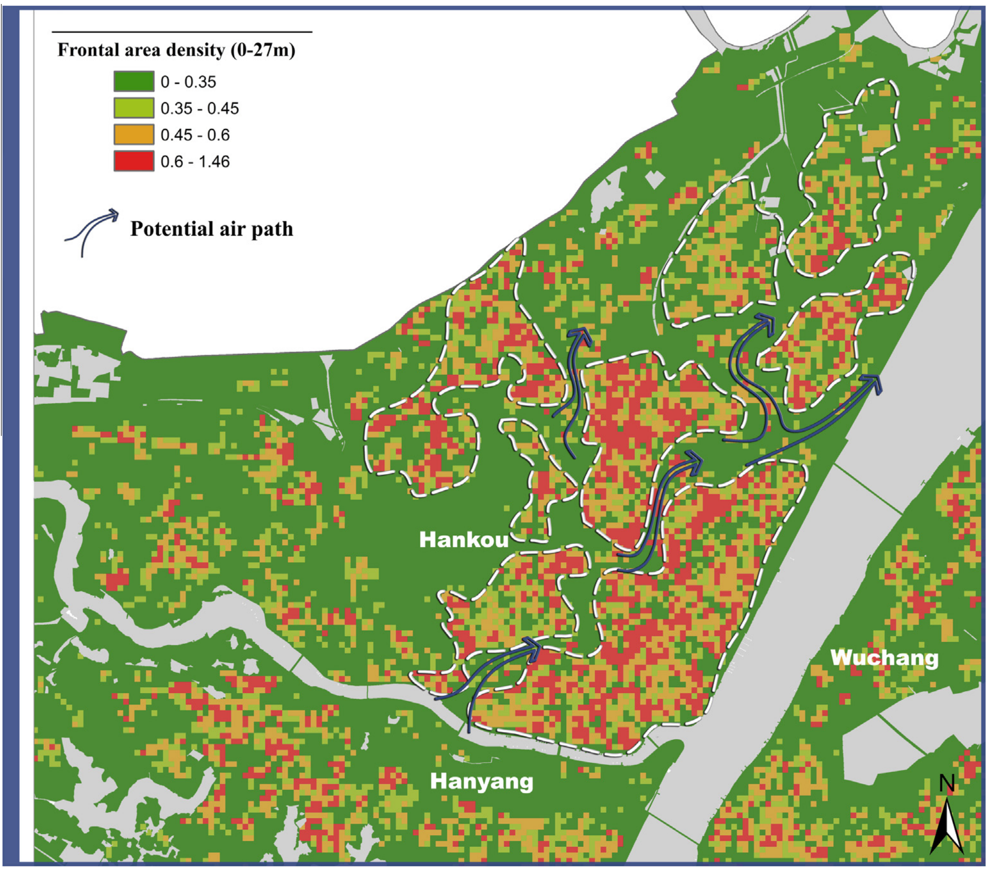

Fig. 6a. Potential air path I (urban scale). White dashed lines marked the boundaries of areas with low urban permeability in Hankou. Potential air path I was represented by blue hollow arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- As shown in Fig. 6a, the areas with low permeability were marked by white dashed line boundaries. The gaps between these boundaries, represented by blue hollow arrows, are characterised by comparatively low surface roughness and are considered as the key areas for the potential air path I. The ground coverage ratio (λ_p) in these key areas needs to be strictly controlled to make sure that air paths are connected to each other – that is, λ_p must be less than 30% (Yoshie et al., 2008). The width of the air path I ranges from several hundred metres to one kilometre.
- The air path II is in the neighbourhood scale, which was detected inside the individual low permeability areas and was represented by blue dashed arrows in Fig. 6b. The potential air path II is important to separate the single and wide low-permeability areas into smaller ones, so that the air can flow into them and thereby mitigate the high intensity of the urban heat island in these areas. The width of the air path II is about 100 m. The values of λ_p at the air paths need to strictly be kept below 30% (Yoshie et al., 2008).

2) Planning goals and mitigation strategies for Wuchang and Hanyang

The low-permeability areas in Wuchang and Hanyang are scattered and smaller than the ones in Hankou. As a result, the planning goal for these two districts is to decrease the urban density of the whole district, avoiding the spread of the small and scattered low-permeability areas. No mitigation

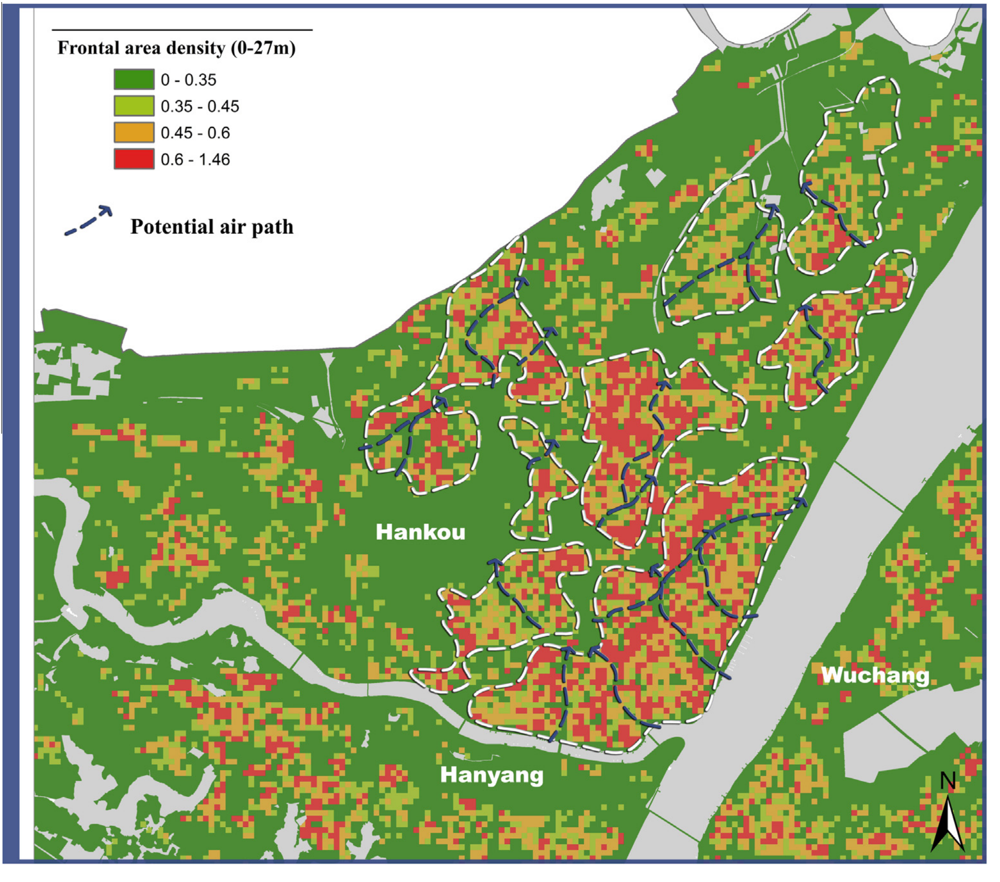

Fig. 6b. Potential air path II (neighbourhood scale). White dashed lines marked the boundaries of areas with low urban permeability in Hankou. Potential air path II was represented by blue dashed line arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

strategies are viable in creating an air path in these two districts. Based on the above planning goal, the corresponding district planning strategies are as follow:

- The land use density of new development projects needs to be controlled by the ground coverage ratio (λ_p), which must be less than 50%, or better yet less than 30%.

6. Conclusions and limitation

In wind tunnel experiments and CFD simulations, the air in the street canyon is treated as the control volume. By contrast, as a viable alternative, the morphological method is an empirical model based on the relationship between urban morphology parameters and experimental wind data. Because of this characteristic, the complicated calculations associated with fluid mechanics can be avoided during the planning process. Urban planners can easily relate the urban natural ventilation knowledge to the urban planning parameters, by using the local 3D building database.

This case study of Wuhan highlights the practical application of the morphological modelling method, from modelling, to the analysis of results, to the establishment of planning guidelines for both master and district planning. As our knowledge of roughness parameters improves and as more experimental data becomes available, the morphological modelling method can be more convincing and has the potential for broader applications.

References

Architectural Institute of Japan, 2008. National Research Project on Kaze-no-michi: Making the Best Use of the Cool Sea Breeze, Newsletter on Urban Heat Island Countermeasures.

Baumueller, J., Hoffmann, U., Reuter, U., 2009. Climate Booklet for Urban Development – References for urban planning. Ministry of Economic Affairs Baden-Württemberg.

Bottema, M., 1996. Roughness parameters over regular rough surfaces: experimental requirements and model validation. J. Wind Eng. Ind. Aerod. 64 (2–3), 249–265.

Burian, S.J., Velugubantla, S.P., Brown, M.J., 2002. Morphological Analyses using 3D Building Databases: Phoenix, Arizona. Los Alamos National Laboratory: LA-UR-02-6726.

Cionco, R.M., 1965. Mathematical model for air flow in a vegetative canopy. J. Appl. Meteorol. 4, 517–522.

Coceal, O., Belcher, S.E., 2004. A canopy model of mean winds through urban areas. Q. J. R. Meteorol. Soc. 130 (599), 1349–1372.

Gál, T., Unger, J., 2009. Detection of ventilation paths using high-resolution roughness parameter mapping in a large urban area. Build. Environ. 44 (1), 198–206.

Grimmond, C.S.B., Oke, T.R., 1999. Aerodynamic properties of urban areas derived from analysis of surface form. J. Appl. Meteorol. 38, 1262–1292.

Hong Kong Planning Department, 2008. Urban Climatic Map and Standards for Wind Environment – Feasibility Study, Working Paper 2B: Wind Tunnel Benchmarking Studies, Batch I. The government of the Hong Kong Special Administrative Region.

Lettau, H., 1969. Note on aerodynamic roughness-parameter estimation on the basis of roughness-element description. J. Appl. Meteorol. 8, 828–832.

MacDonald, R.W., Griffiths, R.F., Hall, D.J., 1998. An improved method for the estimation of surface roughness of obstacle arrays. Atmos. Environ. 32 (11), 1857–1864.

Ng, E., 2012. Towards a planning and practical understanding for the need of meteorological and climatic information for the design of high density cities – a case based study of Hong Kong. Int. J. Climatol. 32, 582–598.

Ng, E., Yuan, C., Chen, L., Ren, C., Fung, J.C.H., 2011. Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: a study in Hong Kong. Landscape Urban Plann. 101 (1), 59–74.

Ren, C., Ng, E.Y.Y., Katzschner, L., 2011. Urban climatic map studies: a review. Int. J. Climatol. 31 (15), 2213–2233.

Wong, M.S., Nichol, J.E., To, P.H., Wang, J., 2010. A simple method for designation of urban ventilation corridors and its application to urban heat island analysis. Build. Environ. 45 (8), 1880–1889.

Yoshie, R., Tanaka, H., Shirasawa, T., Kobayashi, T., 2008. Experimental study on air ventilation in a built-up area with closely-packed high-rise building. J. Environ. Eng. 627, 661–667 (in Japanese).