Green Cantonal Action Plan for Sarajevo

Bosnia & Herzegovina

Study of Urban Ventilation Corridors and Impact of High-rise Buildings

December 2019

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Contents

Abbreviations

Abbreviation	Description
BiH	Bosnia and Herzegovina
C	Instantaneous pollution concentrations
CaSSP	Canton Sarajevo Spatial Plan
CFD	Computational Fluid Dynamics
CiSLUP	City of Sarajevo Land Use Plan
CiSSP	City of Sarajevo Spatial Plan
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
CP	Centre point
SC	Sarajevo Canton
EBRD	European Bank of Reconstruction and Development
ESE	East-southeast
EU	European Union
FBiH	Federation of Bosnia and Herzegovina
$g/(km^2 h)$	Gram per square kilometre and per hour
GBA	Gross Building Area
GCAP	Green Canton Action Plan
GDP	Gross Domestic Product
GHG	Greenhouse Gas(es)
GIS	Geographical Information System
GLUP	General Land Use Plan
HT	Hilltop
k	Turbulent kinetic energy
K/km	Kelvin per kilometre
kg	Kilogram
Ki	Floor area ratio
KM	Bosnia and Herzegovina Convertible Mark
km^2	Square Kilometres
LES	Large Eddy Simulation
L_R	Recirculation length
m	Metre
m/s	Metre per second
MoFTER	Ministry of Foreign Trade and Economic Relations
MPI	Message Passing Interface
Mt	Mega Tonne
MWh	Megawatt Hour
MWt	Megawatt Thermal
NLÖ	Lower Saxony State Agency for Ecology
NO_X	Nitrogen Oxide
NW-SE	Northwest-Southeast

^{o}C	Degrees Celsius
OpenFOAM	Open source Field Operation and Manipulation
Pi	Building coverage ratio
PM	Particulate Matter
PSR	Pressure-State-Response
Q_e/W	Source strength per metre
RANS	Reynolds-Average Navier-Stokes
RS	Reference site
RYG	Red, Yellow, Green
SMG	Specialist Modelling Group
SO_X	Sulphur Oxide
T-flows	Turbulent flows
TOD	Transit-Oriented Development
TOR	Terms of Reference
TRAPOS	Optimisation of Modelling Methods for Traffic Pollution in Streets
TU Delft	Delft University of Technology
U_{ref}	Referent velocity measured
W	West
W_c	Crosswind width
WHO	World Health Organisation
Zo	Roughness height
$\mu g/m^3$	Microgram per cubic metre

Executive summary

This study of urban ventilation corridors and impacts of high-rise buildings is prepared as part of the project “Green Cantonal Action Plan for Sarajevo Canton”. The main aims of the study are to:

- Analyse potential impact on the air flow and quality across the Sarajevo basin by creating new wind ventilation corridors.
- Identify areas/corridors where construction of high-rise buildings should be restricted to improve the air flow and quality throughout the basin.

The study of wind patterns and related pollution levels across the Sarajevo basin is conducted by using Computational Fluid Dynamics (CFD) where terrain and weather conditions are modelled by using GIS[1] and meteorological data.

The study identifies two main air ventilation corridors which are named after their topographical features: Miljacka and Main Road, both oriented along an East-West axis. The air corridor Miljacka is determined by the Miljacka River channel. It stretches from the East where the Miljacka River enters the city (at Bentbaša) until the western part of the city where the river starts to meander (location Halilovici). The air corridor Main Road is formed along the main road that connects the eastern and western parts of the city. The corridor stretches from Marijin Dvor in the East and ends at Stupska Petlja in the West. It is found that the wind intensity along the both corridors vary both in time and space, influenced by complex interaction of air flow and the physical objects in the corridor’s vicinity.

Apart from these two main corridors additional local air corridors were identified. These are significantly shorter than the main corridors but can play an important role in supplying fresh air into the city. These corridors are the South Longitudinal corridor (which coincides with the South Longitudinal road defined by the following streets: Zagrebačka, Grbavička and Zvornička, North Longitudinal road), Alipašina Street (which sits within the Green Belt), Ante Babića Street and Ive Andrića Street (in Alipašino Polje district).

The study concluded that the presence of high-rise buildings in the corridor vicinity reduces wind permeability, thus reducing the supply of fresh air to the corridors. In addition, the recirculation zones in the wakes of buildings would slow down air flow through the corridors if the wakes are penetrating into the corridors. For this reason, the measures are proposed to protect existing routes by which the air is supplied to the corridors as well as to prevent any negative influence of new buildings on the air flow through the corridors.

In order to protect existing air ventilation corridors in Sarajevo the following measures are recommended:

- Prevention of construction of any new buildings in the 20m zone from the bank of the river Miljacka, and from the edge of the Main Road, on each side of the corridor.
- Building height limited to 20m (P+6) in the 200 metre wide zone on each side of the primary ventilation corridors.
- Maximum build coefficient ≤ 1.
- Application of technical guidelines for spatial development and design of structures with the aim of improving the air flow.
- Prevention of construction along the Alipasin Street-Skenderija corridor in the 20mm zone on the right side of the road. Prevention of construction on park areas on the left side of the road.
- Prevention of construction of new buildings within 20m of each side of the Southern Corridor.
- Prevention of construction of new buildings on the surface of 30 m on each side of the ventilation corridors Alipašino Polje 1 and Alipašino Polje 2.

[1] Geographical Information System

To improve the ventilation characteristics of Sarajevo Canton and to mitigate the urban heat island effect, green corridors should be established by merging and upgrading the following existing green spaces:

- Kozija ćuprija – Bentbaša.
- On the North side of Main Road corridor, from Veliki park to Mali Park-Hastahana.
- Greening city yards from Dolina, Fra Anđela Zvizdovića and Kralja Tvrtka Streets.
- Greening a square along Franca Lehara Street.
- Preservation and upgrading existing park areas between Kalemova and Kranjčevićeva Streets.
- Greening the University Campus from Halida Kajtaza street to Hamdije Čemerlića Street.
- Revitalization and greening of the square in front of the train station and the BH Post building.
- Preservation of existing park areas and greening of squares in the area bounded by the streets of Zmaja od Bosne and the railway station on one side, and Lozionicka and Hamdija Cemerlic streets on the other.

1. Introduction

Cities around the world are facing problem of urban pollution and poor air quality which is caused by human-related activities but often are augmented by specific terrain configuration and metrological/weather conditions. Sarajevo has a long history of poor air quality as all the three main contributors to poor air quality are strongly present, strong emissions of pollutants due to human-related activities (traffic, home-heating and industry), city located in a valley surrounded by mountains and hills, and finally weather characterized by often episodes of temperature inversions, especially in the winter times. The situation worsens in the last decade due to the growing trend of urbanisation and the construction of tall buildings along major ventilation routes that create physical barriers for a fresh air supply and reduce natural air ventilation. In such situation, the preservation of the air corridors becomes the highest priority for the city governors. This study is aiming to identify the main routes by which fresh air is transported to the city under the most dominant wind directions and intensities, to explore the impact of the presence of tall buildings on the air ventilation corridor and pollution level in the city.

Therefore, the main objectives of the Study are to:

- Analyse potential impact on the air flow and quality across the Sarajevo basin by creating new wind ventilation corridors; and
- Identify areas/corridors where construction of high-rise buildings should be restricted to improve the air flow and quality throughout the basin.

The study of the existing wind patterns and pollution levels across the Sarajevo basin is conducted by using Computational Fluid Dynamics (CFD) method. The conducted computations are of a field type, meaning that air velocity, temperature and pollutants concentrations are computed simultaneously and interactively in time-dependent three-dimensional space on a computational meshes that provides desired time and space resolution to predict time evolution of pollutant dispersion over the entire solution domain. The terrain is modelled by using GIS[2] while initial and boundary conditions are defined by using meteorological data. The input data were provided by the following Cantonal institutions:

- Institute for Public Health;
- Institute for Planning of Development of Canton Sarajevo; and
- Federal Meteorological Institute.

The Study was developed over a period of six months from March 2019-September 2019.

This document is structured following the Terms of Reference (ToR):

- Chapter 1: Introduction
- Chapter 2: Urban ventilation Corridors
- Chapter 3: Overview of the best practices for protection of urban ventilation corridors
- Chapter 4: Background information of Air Pollution problem in Canton Sarajevo
- Chapter 5: Background information on urbanization trends in Canton Sarajevo
- Chapter 6: Methodology for determination of urban ventilation corridors
- Chapter 7: Computational details
- Chapter 8: Identification of existing air corridors and their characteristic
- Chapter 9: Impacts of tall buildings on air corridors and pollution levels
- Chapter 10: Conclusions and recommendations

Appendix 1 contains presentation of two standard benchmark cases in CFD that have been computed in order to test the accuracy and reliability of the numerical methods undertaken, the turbulence model and the CFD code used in the study.

[2] Geographical Information System

2. Urban ventilation corridors

2.1. Introduction

Currently, more than 50% of the world's population lives in cities. With the continuous expansion of the urban scale, the city's load has increased, quality of the urban environment has dropped, and air pollution has become an increasingly serious issue. Cities across the world are currently facing problems with air pollution, usually the result of emissions from industry, transport and households. Weak air circulation contributes to a greater impact of these emissions. Concern about quality of cities' environment and comfort is rising due to the rapid urbanisation and growth of urban population around the world, especially around the problems of heat stress and air pollution within cities. Nonetheless, discomfort can be significantly minimised in a well-ventilated city, as the ventilation process increases heat lost within the environment to improve thermal comfort, and removes airborne pollutants to improve urban air quality.

A good urban wind environment is an important means to accelerate the spread of pollutant turbulence and increase urban environmental capacity. Therefore, the study of urban ventilation corridors (i.e., wind tunnels or air ducts) proposed for urban ventilation problems has gradually attracted the attention of researchers worldwide who hope to use urban wind paths to improve air quality and mitigate the urban heat island effect and reduce air pollution.

2.2. Literature review

The concept of 'urban ventilation corridor' (also known as a 'wind corridor') originated from a German word "Ventilationbahn" [1]. The German national guideline 'Environmental meteorology climate and air pollution maps for cities and regions (VDI 3787-Part 1)' names it as 'Ventilation Lane' and also gives a clear and detailed definition, which is *the "Area for the mass transport of air near the ground which is preferred owing to direction, nature of the surface and width. Air-directing tracks, also termed ventilation or aeration tracks are intended to facilitate horizontal air exchange processes by means of low roughness (no high buildings, only individual trees), an alignment which is as far as possible rectilinear or only slightly curved, and a relatively large width (as far as possible more than 50 m)*." [2].

A major challenge for government policy makers and managers is to effectively improve air quality, reduce haze, and mitigate the urban heat island effect by using urban ventilation path planning. This aims to avoid the deterioration of the urban wind environment caused by disorderly urban sprawl patterns [3].

A series of policy documents and political actions have shown that countries and local governments in cities have put emphasis on environmental protection and ecological recovery by introducing urban climatic evaluations into town planning and design practices. As a result, many countries and cities around the world are actively developing plans for urban ventilation corridors. Among them is Germany, which began research into this field the earliest, whilst China is currently one of the countries with the largest number of cities conducting such research. The region of Stuttgart published its first Climate Atlas in 1992. The latest Climate Atlas from 2008, managed by the Section of Urban Climatology (Office for Environmental Protection) covers the entire Stuttgart region and shows in detail concentration of air pollutants and the flows of cold air [4]. The Hong Kong Government Planning Department started and conducted an Air Ventilation Assessment study in 2006. The Urban Master Plan of Chengdu included the conduction of the Study of Urban Ventilation Corridor Construction as well as adoption of Planning and Control Ventilation Corridor Strategies.

The research methods and standards for determination of ventilation corridors are varied, and their implementation are varied, often with unsatisfactory results. A group of researchers from the Urban Meteorology Centre of Beijing Metrological Service and The Chinese University of Hong Kong, and planners from the China Academy of Urban Planning and Design and the Beijing Academy of Urban Planning Design have developed a Technical Guide for urban ventilation corridors that recommends a three-step working methodology:

- Step 1 focuses on obtaining a scientific understanding of local urban climatic characteristics and evaluating the potential wind dynamics of built-up areas. For detailed tasks, they include the collection of recommended data (30-year historical meteorological records, building height and building footprint information) and analyses focusing on four key aspects, namely background wind environment characteristics, fine wind environment of the target city´s surrounding areas spatial distribution of urban heat islands, and potential wind dynamics of built-up areas at the pedestrian level.
- Step 2 focuses on creating urban ventilation corridors and developing the corresponding control measures. This step includes three parts: 1) principles of developing urban ventilation corridors; 2) proposals of urban ventilation corridor development and 3) management and control measures of the urban ventilation corridors.
- Step 3 focuses on developing planning and design recommendations, which should have four tasks, including the creation of plans of well-functioning areas, the creation of plans of compensation areas, recommendations for the layout plan of focus areas, and development of the management system of zoning plans based on the climatic impact assessment.

The cities of Guiyang in China and Wroclaw in Poland also conducted studies for ventilation corridor development, which identified how water systems, open and green spaces can be used to expand and improve ventilation corridors. Some measures include adapting the architecture of building blocks to improve airflow, as well as banning construction in places (green open spaces, valleys, urban parks and green areas along rivers) that are a source of fresh air. The results of the study for Hong Kong indicated that parks, as green spaces, not only decrease the thermal load in urban areas, but also provide space for air ventilation.

The main factors affecting the urban ventilation are vegetation, architectural layout, topography and the road system layout. Green spaces have low building density, which is helpful for ventilation. They can create relatively significant temperature differences within the city and form regional wind and air circulation. An integral part of urban ventilation corridor planning is the reasonable planning control of building height and density, and the form of streets inside the city.

3. Overview of the practices for protection of urban ventilation

There are several cities around the world that have dealt with problem of air pollution by through the implementation of urban ventilation corridors. Based on the results of simulations and models, most of these cities decided to enact measures to protect and develop corridors through urban planning, building design, increasing open green spaces and protection of water corridors. Several case studies are presented in this section.

3.1. Hong Kong

With a population of approximately 7.061.200, Hong Kong is one of the most densely populated cities in the world. Intensive construction of tall, dense and "*wall to wall*" building complexes characterised the 20th century cityscape of Hong Kong. The "*wall to wall*" buildings disrupted air circulation and blocked views. At the beginning of the 21st century air pollution in Hong Kong has risen dangerously and started to affect citizens' health, leading to pressure upon developers and the city to find a solution. In 2005, the city's Planning Department published a report, the Feasibility Study for Establishment of Air Ventilation Assessment System [5]. It led to the establishment of a set guidelines on air ventilation for government-funded property projects. Nowadays, when the government approves the construction of building structures this often requires for a gap to be left between structures. In many cases where there is not enough space to leave a gap; a gap is instead created in the middle of the building (examples below in Figure 3.1).

Figure 3.1: Examples of new building structures with a gap in the middle in Hong Kong [6]

3.2. Chengdu city

Chengdu city is located in the central part of China. The city has a population of about 11,000,670 and the city area is 12,390.25 km^2. Ventilation at lower altitudes in the city is often impaired due to its unique topography and natural climatic characteristics. In 2015, ˝The Study of Urban Ventilation Corridor Construction and Planning Strategies in Chengdu˝ was launched. It also serves to support the work of "Urban Master Plan of Chengdu (2016–2035)". The Plan prescribed that "the city's layout should respect the wind environment and local wind circulations". Urban ventilation corridors are formed by ecological buffer zones, greenbelts, roads, rivers, parks and green spaces. The Plan identified six major urban ventilation corridors and 26 secondary ones in the city centre and the new development area in the east. Land use and building forms will be strictly controlled. Suggested strategies to control and manage the urban ventilation corridors in Chengdu are given in Table 3-1.

Table 3-1: Control and management strategies for ventilation corridor planning in Chengdu [7]

	Major Ventilation Corridor	Secondary Ventilation Corridor
Composition	Open green spaces consisting of wedge–shaped green space and greenbelt	Rivers, green space, parks, roads, roadside greening and low and scattered building clusters in the city's built-up area
Width	500 m	≥ 50 m
Length of prevailing wind	5000 m	≥ 1000 m
Width of obstacles perpendicular to airflow	≤ 10% of the corridor's total width	≤ 20% of the corridor's total width
Remarks on management and control	Strict management according to the corridor boundaries, gradual displacement of polluting industries, strict control of ratio of construction land; more greening in built-up areas to further improve the ventilation power of the corridors; strict height and density control in new development areas, evaluation of impact on the meteorological environment, adopting layout that promotes ventilation.	

Combining the results of research on urban meteorological conditions and general principles used in the construction of ventilation corridors, the following principles [7] have been proposed for the construction of a ventilation corridor system in Chengdu:

- Alignment with the prevailing wind direction. Research has shown that the angle between the major ventilation corridor and the prevailing wind should be no larger than 30° to maximise the ventilation and air movement effects in the urban area.
- Combining ventilation corridor construction with ecological planning. When constructing urban ventilation corridors, natural cooling systems with ventilation and heat dissipation functions must be considered. Some examples include green spaces, natural landscape and water bodies. Research has shown that the temperature in a large green city space is 1-2℃ lower than its surroundings. Green spaces also reduce the temperature of neighbouring areas, increasing the speeds of the surrounding winds. The cooling effect can be extended to areas within 3 km. That is why the fresh air from the cold springs identified in the Chengdu landscape and ecological planning can be directed to the urban area by considering the wind characteristics of the city. The main urban ventilation corridor in Chengdu is connected to the circular ecological zone, following the principle of the urban ventilation corridor.
- Make local considerations and respect the city's original features. The city centre of Chengdu is densely structured. There are few expansive green fields, water bodies or roads inside the third ring road. When building an urban ventilation corridor system, the main ventilation corridor should connect with secondary ventilation corridors after reaching the city centre. In that way, the whole urban area can be penetrated.
- Pay particular attention to areas with weak winds and high temperatures. Details of the temperature fields and the wind should be taken into account. The ventilation corridor should penetrate urban areas with lower wind speeds to improve local ventilation. At the same time, warmer areas need to be segmented to enhance local thermal features.
- Take advantage of local circulation. Local circulation may exist in the peripheral areas due to thermal effects. Construction of ventilation corridors can take advantage of these characteristics of the wind field. According to the analysis and numerical simulation of meteorological data in Chengdu, Longmen Mountain areas have a mountain breeze blowing from the mountainous areas into the plains, which is an important source of clean air for the plains.

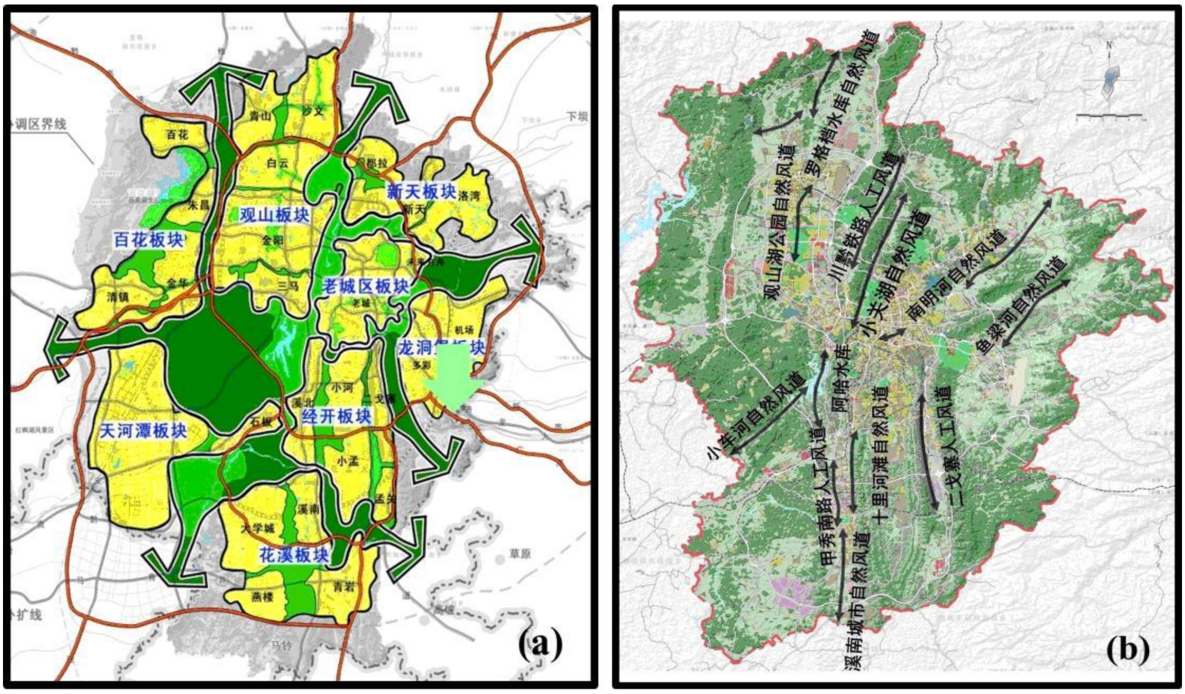
3.3. Guiyang

Guiyang is the capital of Guizhou Province in China. The area of the city is 8,034 km^2 and the city has a population about 4,696,800. An easterly wind and north-easterly wind prevail in winter, and a southerly wind prevails in summer. Wind speed in the city is low, with annual average wind speed of 2.49 m/s.

There are three core guidelines and goals of Guiyang Ventilation Corridor plan:

- Protect the periphery: Guiyang has multiple urban circling shelterbelts and cluster greenbelts, so it is necessary to use these natural green barriers as much as possible to isolate pollution and provide fresh air for the city (Figure 3.2a).
- Dredge the duct: Rivers, reservoirs, wetland parks and valleys are to be integrated to form a continuous air supply duct, such as Shili River natural air duct and Aha Reservoir natural air duct. Also, it is supposed to rely on the railway and urban arterial roads as an artificial construction to form an artificial air duct, such as Ergezhai marshalling station artificial air duct and Jiaxiu south road artificial air duct (Figure 3.2b).
- Control the construction: Strict control of building density, layout, and height should be enforced in order to maintain a reasonable urban ventilation corridor.

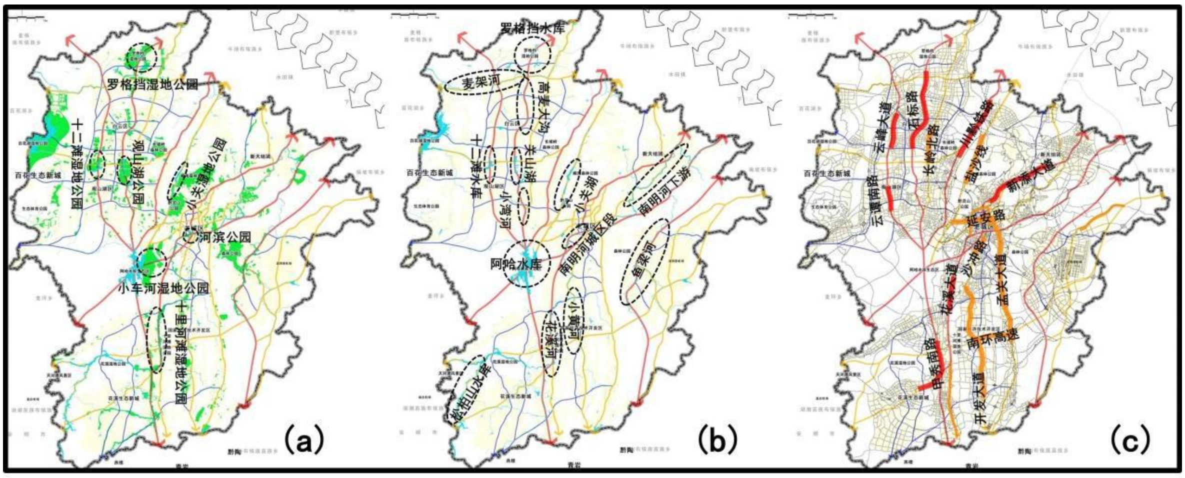
Figure 3.2: The location of urban greenbelt and diagram showing the water system in Guiyang [8]



Guiyang Urban Ventilation Corridor Plan has been designed to:

1. Connect the existing natural green space and water system, enhancing the urban cold area and providing a fresh and clean air for the city.
2. Standardise areas with obvious utilisation problems, and make use of green space, water systems and road networks to plan corresponding ventilation corridors (Figure 3.3).
3. Implement reasonable construction controls in potential ventilation areas, as to prevent excessive construction intensity from blocking urban ventilation corridors.

Figure 3.3: Potential urban ventilation corridors of green area (a), water system (b), and traffic network in Guiyang [8]



3.4. Stuttgart

Stuttgart, the state capital of Baden-Württemberg in Germany, is located in the steep valley of the Neckar. Its landscape is characterised by low wind speeds and weak air circulation. Development on the valley slopes has prevented air from moving through the city, which has worsened air quality and contributed to the urban heat island effect. A Climate Atlas was developed for the Stuttgart region, presenting the distribution of temperature and cold airflows according to the city´s topography and land use. The Atlas comprises maps which show regional wind patterns, flows of cold air, air pollution concentrations, and other relevant information required to inform planners in designing measures for urban climatic optimisation that could inform new projects and retrofits.

More than 60% of Stuttgart's area is green area and more than 39% in total is protected- the highest percentage in Germany [9]. Stream and meadow valleys provide natural green belts which at the same time form preferred pathways for air ventilation. These are represented in Stuttgart by the Nesenbachtal valley, Feuerbacher Tal valley, the Lindenbachtal valley and the Rohrakker valley system [10]. Keeping these valleys free of encroachment by buildings is a well-supported policy, given that aspects of landscape and nature conservation also reinforce urban climatology arguments.

Figure 3.4: Cold air down flow along the ventilation axis left free of buildings at UntererGrund, Stuttgart-Vaihingen [10]

3.5. Overview of the applied measures in selected cities

All mentioned cities applied the following common approach:

- Prepare a detailed climatology study for the area
- Prepare a study on urban ventilation corridors, identify primary and secondary corridors (length and width)
- Apply urban planning measures to protect and develop the corridors:
  - Strict control of ratio of construction land;
  - Strict height and density control in new development areas,
  - More greening in built-up areas
  - Construct green corridors- merge existing parks into a corridor
- Adopt technical guidelines for a building layout and form

When it comes to a technical guideline for building layout and form, useful information could be found in guidelines developed for Chinese cities. The technical guidelines prepared for Chinese cities suggest measures such as:

- Breezeway/Air path
- Building height,
- Building permeability
- Built form including scale of podium/base
- Pavement width and building setback
- Building layout
- Linkage of open spaces
- Street orientation

Breezeway/Air path

As a general rule, the more air ventilation to the streets, the better the environment will be for these dense urban areas. The overall permeability of a district must be increased at the ground level. This is to ensure that the prevailing wind, which travels along breezeways and major roads, can penetrate deep into the district. Breezeways should be provided in order to allow effective air movements into the urban area to remove heat, gases and particulates and to improve the micro-climate of urban environment. This can be achieved by proper linking of open spaces, creation of open plazas at road junctions, maintaining low-rise structures long routes aligned with the prevailing wind direction, and widening of the minor roads connecting to major roads. This approach can also preserve and funnel other natural airflows including land breezes and valley winds, to the developed area.

Figure 3.5: Major breezeways (schematic view)

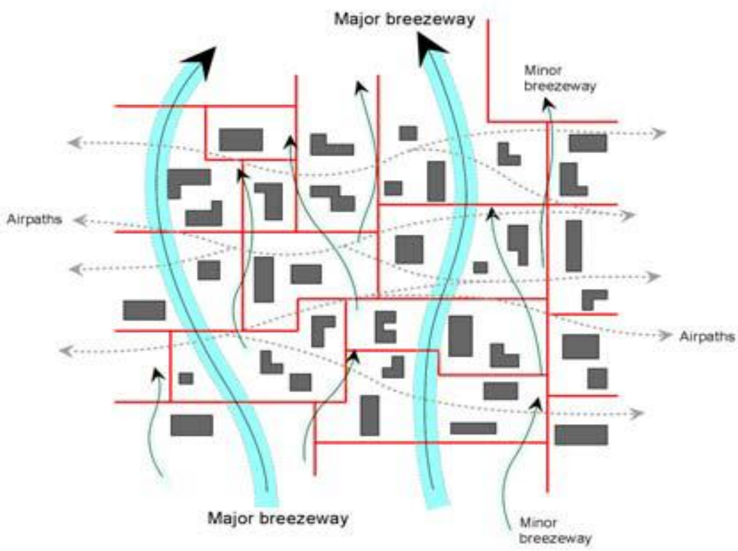


Figure 3.6 - Major breezeways (diagram overlaid on satellite image)

Building height

The heights of the building blocks should vary, with decreasing heights towards the direction where the prevailing wind comes from. It is better to have varying heights rather than similar or uniform height. Stepping building heights in rows would create better wind conditions at higher levels if differences in building heights between rows are significant. Stepping of building heights has been coined as a possible design feature to allow better wind flow [5]. For this to be effective the lower building should be at the windward side of the site and the higher building should be at the leeward side. Wind hitting the taller building will bring the air down, see Figure 3.7 and Figure 3.8.

Figure 3.7: Building height variation in section for better air circulation [5]

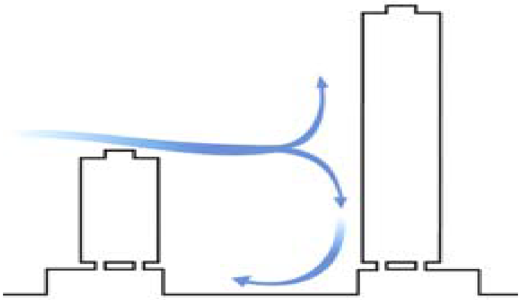
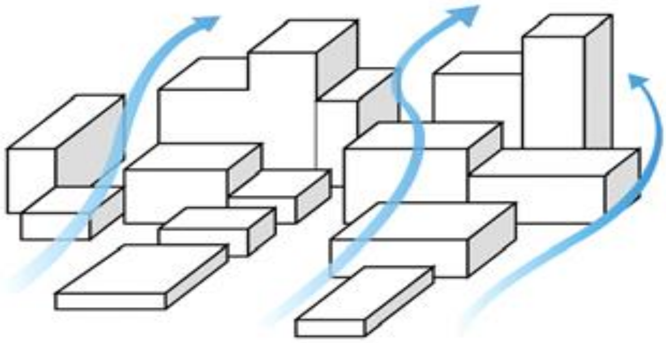


Figure 3.8 - Building height massing showing air circulation [5]



The stepped height concept can help optimise the wind capturing potential of the development itself. A practical example of stepped height buildings is presented in the Kai Tak (Hong Kong) Development Urban Design Guidelines [11]. Difference in height between the first and the second building is approximately 15-20 m, the same as between second and third. The space between buildings has the proportional dimensions and layout to allow air circulation (Figure 3.9).

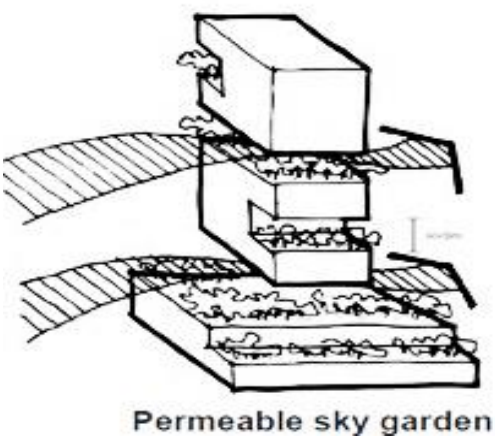
Figure 3.9: Typical juxtaposition of adopting building height variety within the site [11]

Building permeability

The provision of permeability/gaps nearer to the pedestrian level is far more important than at higher levels. It is useful to create permeability amongst housing blocks and to try to create voids at ground level to improve ventilation for pedestrians. This will improve not only the air movement at the ground level but also the channelling effect created by the void helps to improve the ventilation performance for those residential units at the lower floors. Creation of openings in the building blocks to increase their permeability may be combined with appropriate wing walls that will contribute to pressure differences across the building facades and will permit the air to flow through the openings of the buildings. The openings on the buildings should not be less than 3m wide, so that the air could flow through.

Hysan Place is a 40-floor building in Hong Kong, which received several awards including a Green Building Award. The building was taken as an example of good application of openings on buildings. Diagrams showing the approach to permeability at Hysan Place are shown in Figure 3.10.

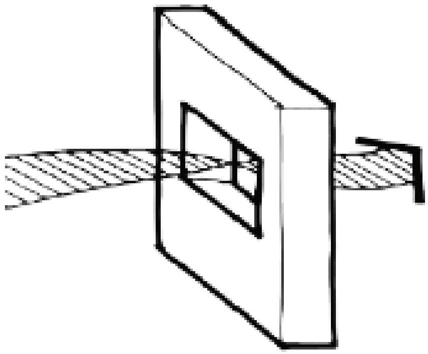
Figure 3.10: Schematic representation of openings on Hysan Palace [12]



There are a lot of different types of building gaps/openings. For example, one bigger opening can be positioned in the middle of the building. The Kai Tak Development is an example of building which has a characteristic high opening at its centre, through which air flows (Figure 3.11 and 3.12).

Figure 3.11: The opening at the centre of building and Kai Tak Development example [12]

Figure 3.12 - Diagram showing air flow permeability through a gap [12]

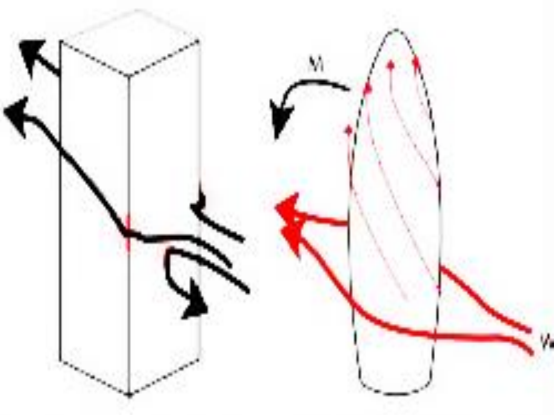


Wind flow and built form

Different aspects of the building form can cause increment or reduction in wind effects. Buildings with rounded forms, rather than rectangular forms with flat surfaces, offer less wind resistance and improve air currents. A major problem with high buildings is that air currents sweeping around them create whirlwinds. The Specialist Modelling Group (SMG) advise the architects to use computer models which simulate a building's aerodynamic properties. The model showed that a cylindrical shape responds better to air currents than a square one and reduces whirlwinds as it does not create an airflow barrier **(**

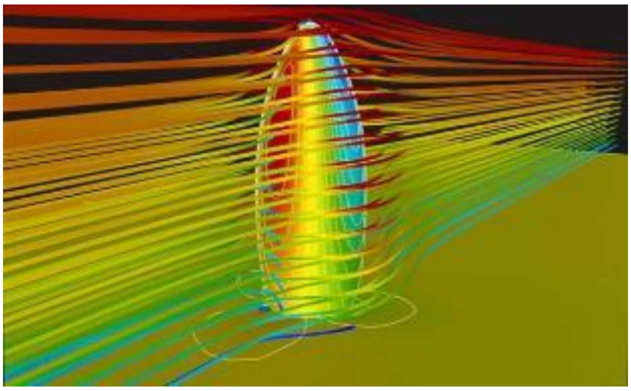
Figure 3.13**).**

Figure 3.13: Wind movements around rectangular and cylindrical buildings [13]



30 St. Mary Axe, or most commonly known as the Gherkin, is one of the projects that SMG was involved with and is a prime example of how geometry of the building form was designed to satisfy wind environment whilst providing innovative architecture. It is located in the City of London and was built in 2004. The overall cylindrical shape allows for the wind to move around the building; flowing air is deflected around the curve and does not encounter obstacles head on, which is not the case with flat buildings. (Figure 3.14)

Figure 3.14: View of Gherkin and model of air currents around Gherkin [14]



Scale of podium

The podium (or building base) is the primary interface between the tall building and the surrounding streets and public spaces. It therefore has the greatest impact on how pedestrians interact with building and how the building fits within the street level environment [15]. A podium with large site coverage blocks the wind and minimises the air volume near the pedestrian level. For large development/redevelopment sites, particularly in existing urban areas, it is critical to increase permeability of the podium structure at the street levels by providing some ventilation corridors or setback parallel to the prevailing wind. A terraced podium design should be adapted to direct downward airflow. This can enhance air movement at the pedestrian level and disperse the pollutants emitted by vehicles (Figures 3.15 and 3.16).

Figure 3.15: Proper form of podium for good air circulation [5]

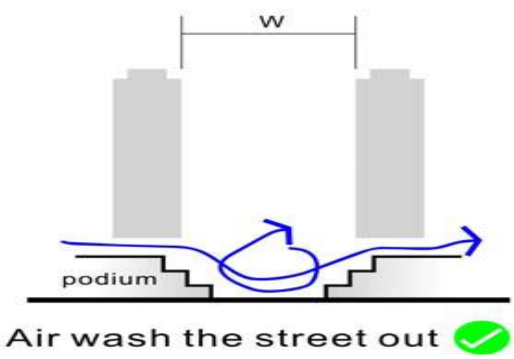
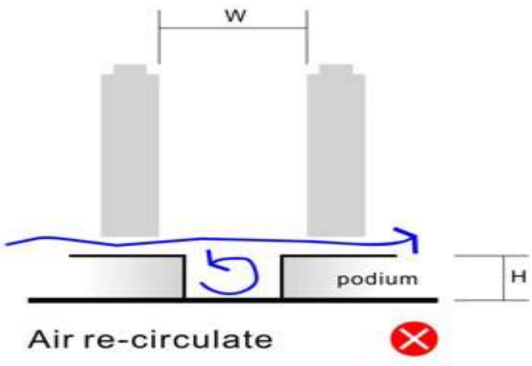


Figure 3.16 - Inefficient form of podium for good air circulation [5]



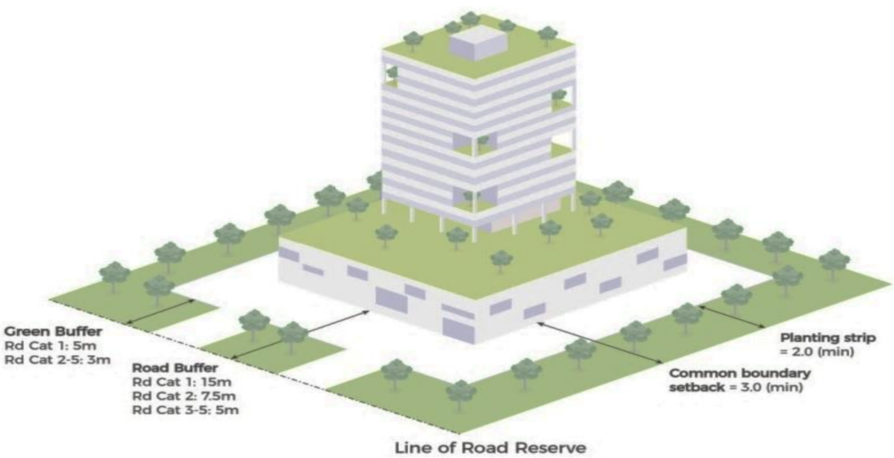
In the modern architecture, the stepped podium is used very effectively. A tower, which is currently under construction in Shanghai city centre, is an example of a large tower design that will feature a stepped podium mall with lush terraces that are open to the public, extending the green space towards the south, allowing for good ventilation (Figure 3.17).

Figure 3.17: Planned tower design in Shanghai with stepped podium [16]

Pavement width and building setback

Pavements should be of adequate width to accommodate pedestrian flows and to allow reserves for utilities installations and street trees or landscaping. In older urban areas where pavements are narrower or of inadequate width to serve present needs, effort should be made to widen these pavements through building setback or reducing coverage of podium when redevelopment takes place [17]. In new development areas, good design and wider pavement should be provided for the creation of a high-quality pedestrian environment. Setbacks can be created by zoning restrictions, ordinances and building codes laid out by local governments. A zoning law may, for instance, specify a 3m setback, which means that there must be at least 3m between a road and the plot boundary for a building. Considering Mong Kok as an example, it is recommended that building setback should be about 3-5m at both sides of a typical street. This is a practical iterative approach to improving the urban air ventilation for the entire district in long term, but would be more immediately possible to implement when large land parcels are redeveloped, see Figure 3.18.

Figure 3.18: Building setback from boundary [18]



In terms of integration with other aspects of sustainable urban planning, it is noted that large setbacks can significantly alter urban form with large separation between buildings, making pedestrian journeys much longer, reducing effectiveness of active frontages, and creating large areas of poorly used public realm space. Integrated urban design guidelines covering larger areas, and taking account of integrated green infrastructure, often represent more effective means of encouraging climate responsive urban form, including enhanced urban ventilation, than plot-based regulations. Spacing of buildings can also have substantial effects on outdoor thermal comfort in terms of street and open space shading and building over-shading [32].

Building layout

Positioning the building according to the prevailing wind direction is an effective design approach to improve air movement. Wide gaps should be provided between building blocks to maximise the air permeability of the development and minimise its impact on wind capturing potential of adjacent developments. The arrangement of the blocks should be staggered such that the blocks behind are able to receive the wind penetrating through the gaps between the blocks in the front row, creating breezeways to ventilate and flush out pollution. In order to maximise the wind availability to pedestrians, towers should preferably touch the podium edge that faces the main pedestrian area as to enable most of the downwash wind to reach the street level. Kai Ching Estate, Hong Kong, is an example of urban construction that allows air to flow without major obstacles. Between each building there is a passage through which air can flow (Figure 3.19).

Figure 3.19: Air flow between buildings in the Kai Ching Estate, Hong Kong, China [12]

Linkage of open spaces

Open space linkages are linear, undeveloped (or less developed) corridors that contain natural features, trails or open spaces that connect existing or proposed open space areas. They can form a link between multiple residential neighbourhoods. Open space linkages typically follow creeks, streams riverbanks or former linear infrastructure routes, and these linkages can be multi-modal. Where possible, open spaces may be linked and aligned in such a way to form breezeways or ventilation corridors. Structures along breezeways/ ventilation corridors should be low-rise. For urban ventilation corridors, open space and width are equally important. (Figure 3.20)

Open space is often determined by building size, positioning and layout, so it is important to establish corridor construction land planning. The planning of open spaces should consider the main ventilation corridor and set aside a significant area of open space, important to roads, squares and green belt. Construction land proportion should not exceed 20% and the buildings should be mostly lower with low density. The draft Hong Kong Urban Climatic Planning Recommendation Map provides a plan for appropriate linkage of open spaces. (Figure 3.21)

Figure 3.20: Diagrammatic connection between open spaces [5]

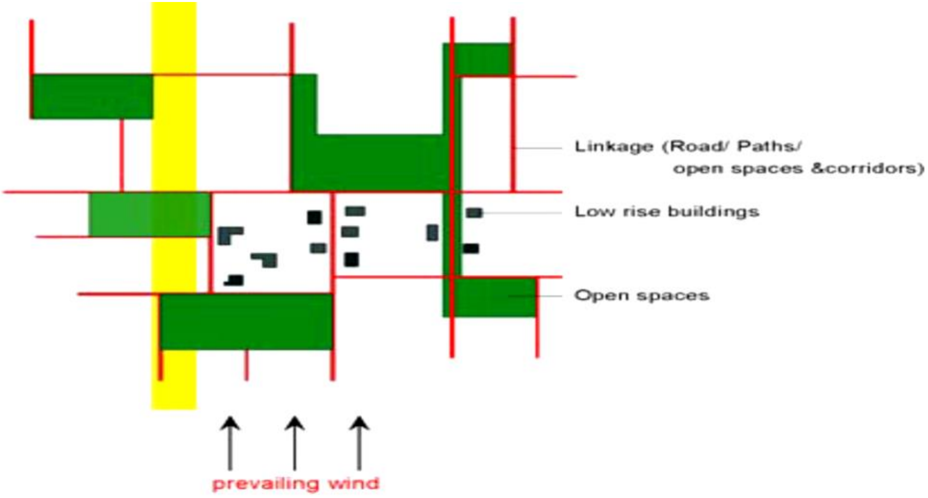
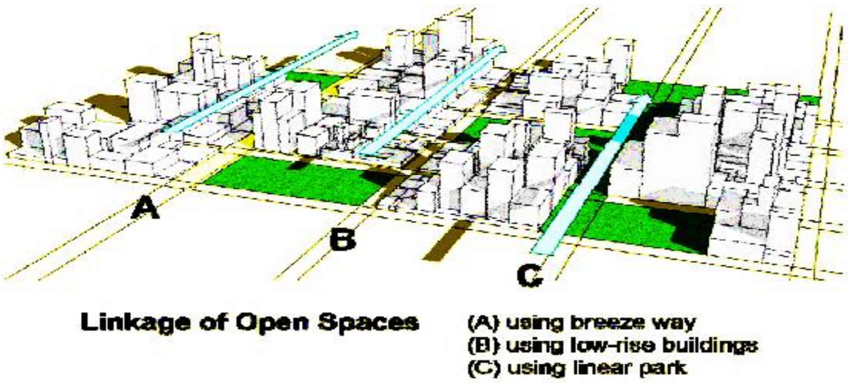


Figure 3.21: Building setback and building permeability, air paths, open spaces (air ventilation connectivity) and greenery [19]



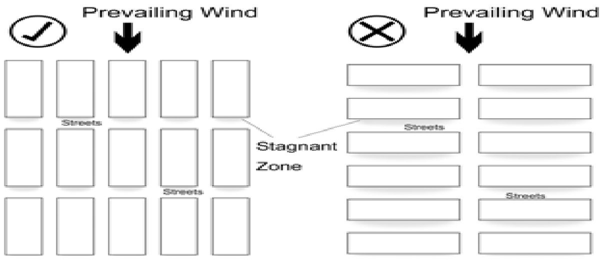
While indoor air ventilation criteria are well established (EPA and ASHRAE Standard) and in practical use for quite some time, outdoor air ventilation criteria are still not defined in a form of any international recognised standard. However, in recent years cities have started to perform Air Ventilation Assessments (AVA) (e.g. Hong Kong by Edvard Ng, 2006) aiming to better understand existing wind patterns, their correlation to pollution levels and wind comfort, and to define performance criteria needed for considering the impact of development on wind environment. The AVA studies are used for smarter urban planning that would not damage wind environment or increase health risks due to poor air quality. As the morphology and microclimate of cities around the world vary widely, performance criteria that would consider the impact of development on wind environment have to be defined uniquely according to their individual contexts.

A multi-function, multi-benefit approach to green infrastructure requires a concerted, integrated strategy at the urban planning area level. The supports optimisation of the various benefits of green infrastructure: air movement / ventilation / air pollution, biodiversity, runoff attenuation, pedestrian/cycling movement, public amenity (recreation, play, education), noise attenuation, energy generation (thermal heat source / store) [32].

Street orientation

Through suitable street orientations it is possible to enable penetration of winds to the heart of the city. When streets are perpendicular, or near-perpendicular, to the wind direction, and the buildings lining the streets form long rows so that urban layout presents the highest resistance to the urban wind. An array of main streets, wide avenues should be aligned, or up to a maximum of 30˚ to the prevailing wind direction, in order to maximise the penetration of prevailing wind through the district. (Figure 3.22)

Figure 3.22: Scheme of proper and irregular street orientations [5]



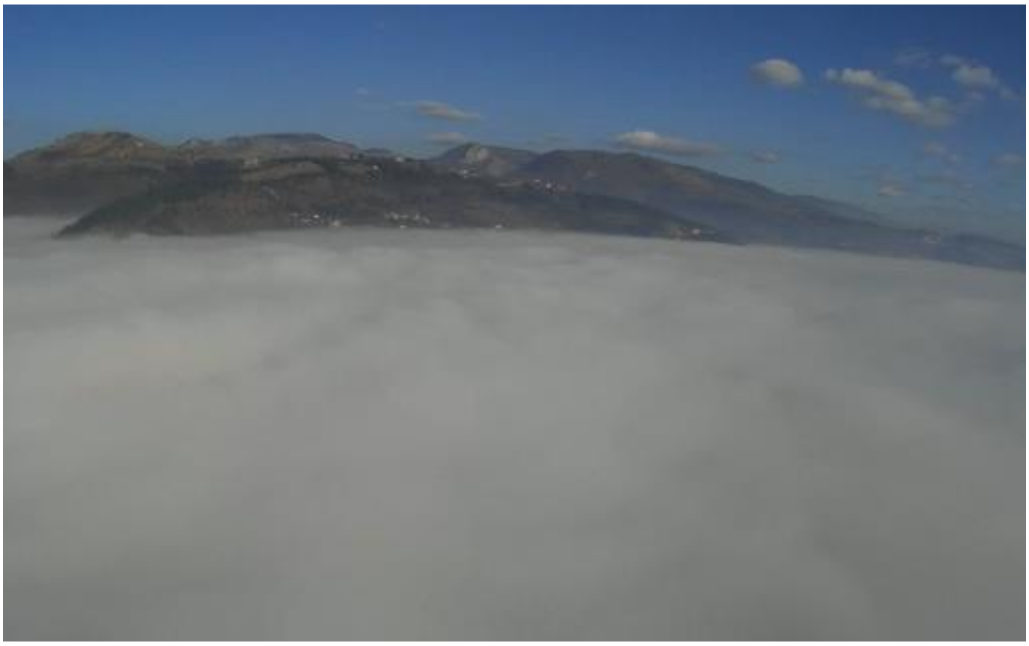
4. Background of air pollution problem in Sarajevo Canton

Canton Sarajevo (CS) faces high air pollution, especially in the winter months, during which trend analysis shows exceedance of daily limit values for air pollutants such as PM_{10}, SO_x and NO_x. According to annual reports on air quality [20], all monitoring stations have recorded a significant increase of daily exceedances of PM_{10} limit values (>50 μg/m^3) (FBiH and EU limit value).

The sources of emissions in CS with the greatest impact on air quality are the residential and transport sectors [21]. Only 34% of the housing sector in CS is connected to the district heating system (which uses natural gas as its main fuel) while the remainder of the stock is equipped with central boiler rooms that consume various primary fuel sources such as natural gas, electricity, liquid and solid fuels and individual furnaces combusting gas, coal, firewood or pellets including electricity based ones. Sloped areas of the Canton, dominantly comprised of individual houses, are not connected to the district heating network and represent a major contributor to air pollution [22]. As a result of the change in types of fuels used in residences of CS (e.g. fuel such as natural gas is being replaced by coal and firewood due to shifting resource costs), sources of air pollution are unsteady.

Furthermore, CS is a basin surrounded by mountains, which results in an additional negative impact on air quality status due to occurrence of a heavy fog that converts into smog when mixed with high levels of pollutants. The airflow impeding topography, combined with the typical climate of the region, promotes a climatic phenomenon known as a temperature inversion. Temperature inversions have a tendency to trap air pollution at ground level for extended periods of time (Figure 4.1) [23].

Figure 4.1: Pollutants above the city of Sarajevo as a consequence of temperature inversion [23]

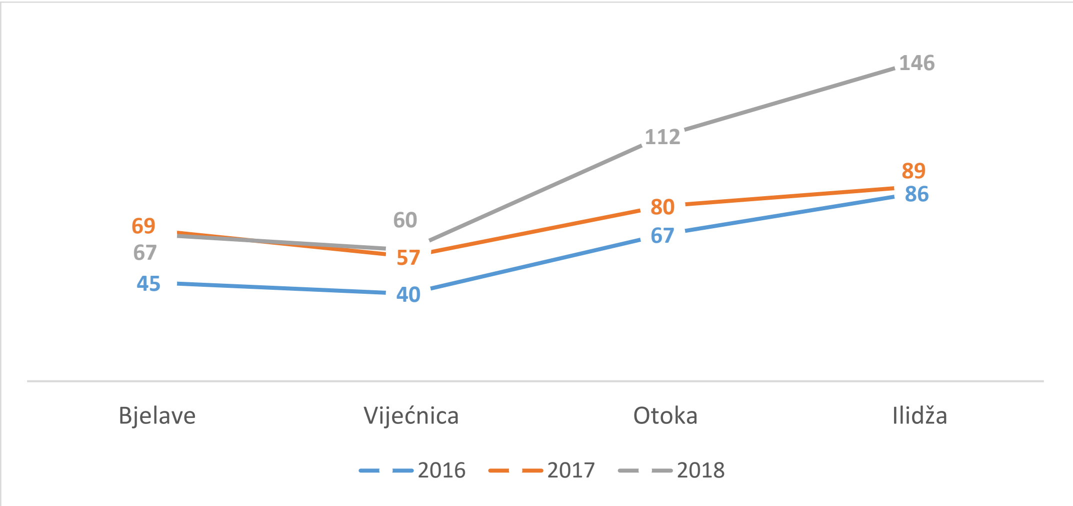


Monitoring of air quality in Canton Sarajevo is the responsibility of the Federal Hydro-Meteorological Institute (whose monitoring stations are located in Bjelave and Ivan Sedlo) and the Public Health Department of Sarajevo Canton (monitoring stations Otoka, Vijećnica and Ilijaš). The analysis of exceedance of air quality limit values in Canton Sarajevo was conducted based on data of the annual report on air quality in the Federation of Bosnia and Herzegovina for the period of 2016-2018. The monitoring stations that were analysed are: Bjelave, Vijećnica, Otoka and Ilidža. Also, this analysis shows the number of daily exceedances of pollutants PM_{10}, NO_2 and SO_2, that are in excess of the limit values set for the protection of human health according to entity (FBiH) air quality legislation which is aligned with EU air quality standards [45].

Exceedance of PM_{10} daily limit values

Most of the air quality monitoring stations in CS recorded annual average PM_{10} concentrations close to or higher than ambient air quality limit values. Over the period 2016-2018, the largest number of daily exceedances (146) was recorded at Ilidža monitoring station. For reference, the limit values are not to be exceeded on more than 35 days per year according to entity (FBIH) air quality legislation, which is fully aligned with EU air quality standards. Furthermore, the monitoring station with the second largest number of daily exceedances of PM_{10} limit values was Otoka (112) during 2018.

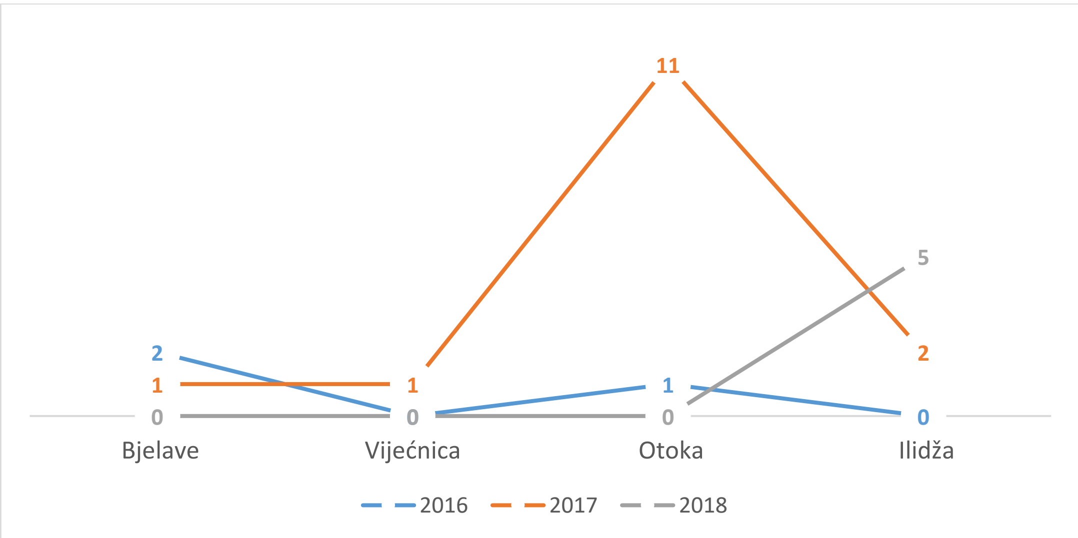
Figure 4.2: Number of daily exceedances of PM10 limit values (>50 µg/m³) [24]



Exceedance of SO_2 daily limit values

In 2018, no daily exceedances of SO_2 daily limits were recorded at Bjelave, Vijećnica and Otoka monitoring stations, while the largest number of daily exceedances (11) was recorded at Otoka in 2017 with a downward trend (Figure 4.3).

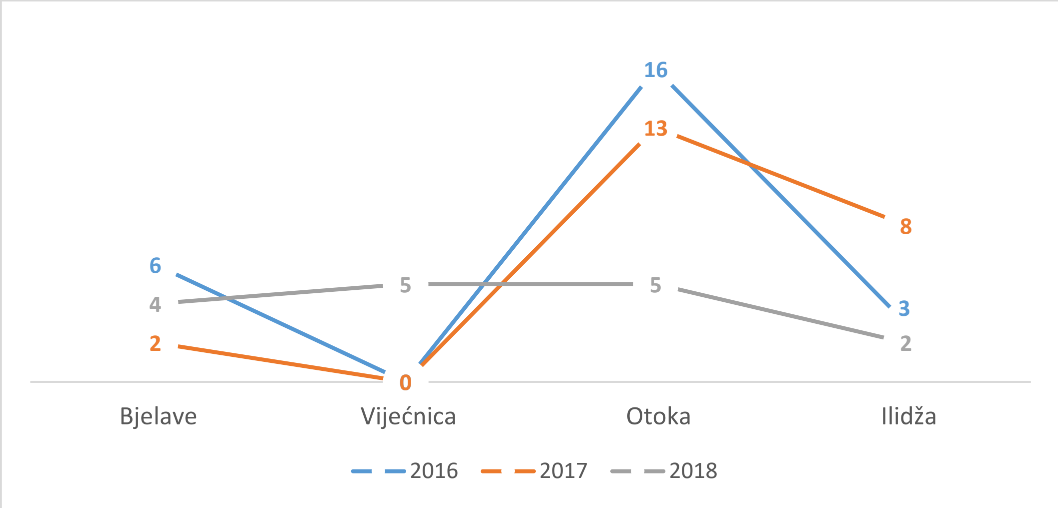
Figure 4.3: Number of daily exceedances of SO_2 limit values (>125µg/m³) [24]



Exceedance of NO_2 daily limit values

The largest number of daily exceedances of NO_2 limit values (16) was recorded at Otoka monitoring station (during 2017) with a downward trend since (Figure 4.4).

Figure 4.4: Number of daily exceedances of NO_2 limit values (>85 µg/m^3) [24]



The results of air quality analysis in CS indicate that Otoka monitoring station records the largest number of daily exceedances of PM_{10}, SO_2 and NO_x limit values. When it comes to PM_{10} exceedances, the stations (Otoka and Ilidža), which show upward trends, are sited in some of the most prominent locations dominated by local traffic and residential buildings.

Air quality exceedances in CS are characteristic of the winter season (January, February, March, October, November and December) especially when it comes to PM_{10} concentrations, according to the data from the annual report on air quality (Figure 4.5).

Figure 4.5: Review of the mean daily PM_{10} concentrations at Otoka monitoring station in 2018 (ug/m^3) [24]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
JANUAR		71	68	80			82	97	69	25	30	34	16	36	73	79	22	63					105	136				198	227	209	
FEBRUAR		21	34	40	76	147	70	42	67	87	52	114											77	34	20	30	50	57			
MART	149	252	31	64	102	75	47	38	92	100			18	20	18	33	38	17	26	31	35	35	37	62	76	54	55	74	57	20	15
APRIL			32	66	71	26	37	49	49	40	66	88	56	59	78	104	75	35	42	36	35	33	36	35	48	50	39	45	25	41	
MAJ	43	40	38	19	34	25	35	32	35	41	37	31	17	19	10	7	13	18	24	25	25	23	27	26	35	36	29	32	28	30	32
JUNI	39	26	24	23	20				19	24	38	39	22	15	7	14	20	23	26	31	34	20	15	17	26	24	16	19	26	21	
JULI	16	28	42	44	32	34	21	21	24	25	27	40	33	31	31	34	16	30	32	33	32	27	22	24	27	34	26	27	30	31	33
AVGUST	37	40	39	36	26	34	39	40	42	43	52						25	36	42	36	38	35	27	23	25	19	13	26	38	34	40
SEPTEMBAR	36	35	28	21	20	33	26	24	29	28	29	36	39	36	40	28	27	35	38	43	49	46	36	28	16	19	39	43	45	22	
OKTOBAR	39	32	46	43	72	54	26	30	35	50	54	63	54	69	65	68	73	78	88	66	35	32	57	62	36	83	31	9	18	25	59
NOVEMBAR			81	115	142	98	99	86	110	114	97	124	145	118	76	38	19	30	47	71	69	65	56	122	138	56	44	23	20	40	
DECEMBAR	146	242	276	258	59	138	225	179	65	70	63	110	119	103	30	81	159	69	117	313	414	159	214	80	19	73	208	271	351	224	28

exceedance

without exceedance

5. Background information on urbanisation trends in SC

5.1. The history of urban planning in SC

Urbanisation of today's Canton Sarajevo, and the pre-war entity City of Sarajevo, began with the adoption of General Land – Use Plan (GLUP) in 1965 and was followed by:

- The City of Sarajevo Spatial Plan for the period 1986 – 2000/2015 (CiSSP),
- The City of Sarajevo Land Use Plan for the period 1986 – 2015 (CiSLUP),
- Canton Sarajevo Spatial Plan for the period 2003 – 2023 (CaSSP),
- The Amendments of Canton Sarajevo Spatial Plan for the period 2003 – 2023 – phase "A",
- The Amendments of Canton Sarajevo Spatial Plan for the period 2003 – 2023 – phase "B".

In the last twenty years or more, urban planning in CS has mainly followed amendment procedures of existing development spatial planning documentation, mostly CaSSP and CiSSP.

Sarajevo, as a longitudinal city, which is being developed westwards and northwards, has based its construction primarily towards these two directions since the ancient times.

The Land Use plan prescribed a maximum of four-storey buildings within the urban area of Sarajevo, and a building coverage ratio (Pi) of 26%. Building coverage ratio (Pi) is the proportion of the floor area of an object relative to the parcel surface.

The General Land Use Plan introduced the principle of enlarging open space between the residential buildings if the planned number of storeys exceeds an average of four. This principle was implemented when planned new neighbourhoods. The City of Sarajevo Land Use Plan for the period 1986 – 2015 (CiSLUP) enacted a maximum floor area ratio[3] ≤ 1 for the City's urban area and increased maximum average floor number to six storeys. Floor area ratio (Ki) is the ratio of gross construction area of the building (GBA) and the plot area, where GBA means the total developed area of all above ground floors of the building. The principle of enlarging distances between the planned, mostly residential, buildings in planned neighbourhoods, defined by GLUP, remained in place in the CiSLUP. It is important to emphasise that GLUP and CiSLUP highlighted the problem of temperature inversions in Sarajevo, as well as unfavourable basin geomorphology as two factors which affect diminished natural ventilation of the city, which needs to be taken into consideration in the future development planning concepts.

The spatial planning projection for residential function in Canton Sarajevo Spatial Plan for the period 2003 – 2023 (CaSSP) is based on the following principles:

- a commitment to improving the quality of life
- rational land use and environmental protection
- canalizing the housing function through planned spatial development directions
- development according to adopted distribution of projected number of inhabitants for 2023
- to define the building land according to availability of potential locations

The CaSSP minimises building land mobilisation and requires detailed spatial planning documentation to be revised, according to the needs of the projected number of inhabitants in 2023 distributed across the SC municipalities. The City of Sarajevo and Canton Sarajevo do not have approved Land Use Plans.

[3] Floor area ratio (Ki) is the ratio of gross construction area of the building (GBA) and the plot area, where GBA means the total developed area of all above ground floors of the building.

5.2. Recent changes in urban planning concept

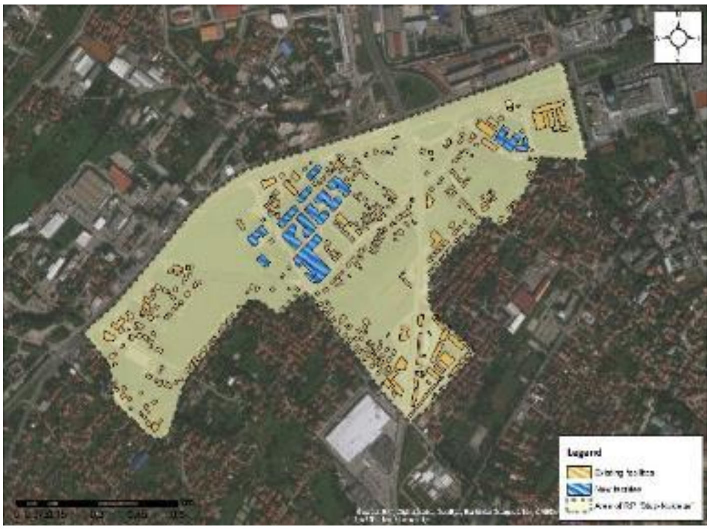
In the Amendments to the Canton Sarajevo Spatial Plan for the period 2003–2023 – phase “A”, the residential area is being enlarged by changing several industrial zones to combined commercial and residential zones, which have been executed dominantly as residential areas, yet without previously adopted amendments of City of Sarajevo Land Use Plan for the period 1986 – 2015.

Non-adoption of the aforementioned amendments to the Land Use Plan was the reason for not having several urban and technical guidelines, such as average number of floors, building coverage ratio, floor area ratio, number of inhabitants in planned combined commercial and residential zones. This was particularly pertinent in the creation of detailed spatial planning documentation for the formerly industrial areas repurposed to commercial and residential uses. The analysis of certain regulatory plans and their implementation shows a constant trend showing an increase of floor numbers for predominantly residential buildings, as well as noticeable change to other urban parameters and metrics such as Building coverage ratio (Pi) and Floor area ratio (Ki). For example, the Regulatory Plan “Marijin Dvor City Centre” (2007) [46] increases the building coverage ratio from 7.9% to 19.83% and the floor area ratio from 0.4 to 0.95 [24]. The following figure shows the existing constructed facilities in the given area, where orange marked facilities are those created during the implementation of Regulatory Plan “Marijin Dvor City Centre”, while blue marked facilities are those facilities created after the adoption of the regulatory plan.

Figure 5.1: Regulatory plan of the City Centre “Marijin Dvor” [46]

Another example of urban change in Canton Sarajevo is area of Stup. The building coverage ratio in the area of Regulatory Plan “Stup-Nukleus” is 13.43%, which is almost 4% higher than in 2010. Most of the facilities were built on green spaces, including dense high-rise development with small distances between buildings. Overall densities have increased due to lack of regulation.

Figure 5.2: New facilities planned within the Regulation Plan "Stup-Nukleus". [47]



5.3. Construction practices

In terms of building layout and form, Sarajevo shows some examples of very good construction practices. In terms of building position the Hrasno neighbourhood has some tower blocks, which represent good building disposition in terms of urban ventilation (Figure 5.3). Four skyscrapers are arranged in a grid of two columns and two rows and there is a wide space between each tower.

Figure 5.3: Examples of skyscrapers in the Hrasno neighbourhood [48]

Few examples exist in Canton Sarajevo of high-quality networks of open spaces. Dobrinja settlement has low-rise buildings and several parks located between building blocks, as well as wide walkways and side roads (Figure 5.4). Open spaces in Dobrinja (parks in this case) are connected by passages between building blocks, and with walkways. Due to the lower height of buildings and the larger number of open spaces, the wind speed is higher than in neighbourhoods where the construction of buildings and the positioning of open spaces are not properly considered.

Figure 5.4: Satellite view of the Dobrinja as an example of good linkages of open spaces [49]

On the contrary, although the Alipašino Polje area has several large parks, there are a number of high-rise buildings (many of which have more than 10 floors), which are densely laid out. Alipašino Polje-Phase A and Stup have built tower blocks without adequate gaps or passages between buildings (Figure 5.5 and Figure 5.6). As a result, the air in these areas flows at lower speeds.

Figure 5.5: Tower blocks in Alipašino Polje [50]

Source: uskinfo.ba

Figure 5.6 - Tower blocks in Stup [51]

Source: sarajevo.co.ba

Sarajevo has no prominent examples of building height variation within a development. Typical buildings onto which a height variation rule could be applied are those located in Čengić Vila and Otoka. (Figure 5.7) These buildings are perpendicular to the prevailing eastern wind. Due to the fact that there is no variation in the heights of buildings the airflow in these neighbourhoods is impeded.

Figure 5.7: Example of some buildings in the Čengić Vila neighbourhood

There are only a few buildings in Canton Sarajevo that have a rounded or curved shape. Among them is Avaz Twist Tower. This building has a helical shape and vertical columns positioned in a circle with twisted facades hanging from protruding floors [26]. Its facade spirals 2.8 degrees per floor, and in total rotates at 90 degrees across its full height. The Avaz Twist Tower does not have a rounded shape like the Gherkin example, but still has a low airflow drag coefficient. However, most buildings in Canton Sarajevo have a square shape, obstructing the airflow around them.

Figure 5.8: Avaz Twist Tower [52]

Figure 5.9 - Examples of typical flat buildings in Canton Sarajevo

Canton Sarajevo does not have many tall buildings with expressive podiums. Some examples are the SCC Centre, the Parliament of BiH and Bosmal City Centre (Figure 5.10). Each building has a podium constructed as a cube without recommended terrace form.

Firstly, it would be preferable for these towers not to have a simple rectangular podium, but rather to leave an empty space which would allow air to flow. Secondly, in order for the air to flow efficiently, it would be more practical to construct terraced podium.

Figure 5.10: Bosmal City Centre

When it comes to building setbacks, there are some examples of buildings in Canton Sarajevo that have larger setbacks. The Parliament of Bosnia and Herzegovina (Figure 5.11) has a fairly wide setback which contributes to the circulation of air. Alta Shopping Centre also has a setback, but it is narrower than that of the nearby Parliament building (Figure 5.12). Sarajevo City Centre could have been another good example of building setback, but the setback is limited by parking and one side is set very close to the street. It would be useful for urban ventilation to increase number of building setbacks, similar to the example of the Parliament building.

Figure 5.11: Example of setback at the Parliament of Bosnia and Herzegovina [53]

Figure 5.12 - Example of setback at the Alta Shopping Centre [54]

In Canton Sarajevo, non-building areas usually include parks with greenery, sports fields or playgrounds. Great Park, located on the street Maršala Tita, is the biggest green area in city centre. The park provides fresh air and coolness during warm summer days. Canton Sarajevo has a large urban park at Centre Safet Zajko, located in the municipality of Novi Grad, which stretches along the River Miljacka. Its large area consists of green surfaces, water pools, playgrounds and sport fields. Whilst the park provides a good recreational resource, it is also a place which retains fresh air. Other examples of urban parks are the Park of Lightness, located close to the Druga gimnazija high school, and Hastahana Park located in Marijin Dvor. These spaces are important in combining the cooling effect of parks with the pollution caused by surrounding roads, building a small urban ventilation system in the areas where parks are located. Any larger open area, set away from traffic thoroughfares, may be expected to have lower ambient pollution levels from road traffic (due to the local dispersion gradient), and will help with wider air flow. More tree vegetation can help to absorb some pollutants. Soil and vegetation can help to reduce the urban heat island effect.

Figure 5.13: Urban parks in Canton Sarajevo [55]

Non-building areas also include several green spaces/undeveloped sites, such as in the Alipašin Most neighbourhood, close to the Radio-Television of Federation of Bosnia and Herzegovina building. The space located in Dobrinjska street in Stup (Figure 5.14) provide another example of this resource. These spaces are located close to new construction sites and it is very important to preserve them as non-building areas, as they are situated in places where the prevailing wind flows. Recently, the number of buildings and construction sites in Canton Sarajevo has increased and the number of green areas has declined. It is essential to preserve existing green spaces and prohibit building construction in important airflow/ventilation areas where possible. It is advisable to increase the number of urban parks such as Safet Zajko Centre or Hastahana Park, because in addition to be used for recreation, they are also beneficial for reducing pollution, cooling effect and fresh airflow.

Figure 5.14: Green plains and surfaces in Alipašin Most and Stup [56]

Air pollution and heat islands are major challenges for Canton Sarajevo and therefore it is essential to overcome them. Built-up pollution coefficients in the urban area of Sarajevo in certain zones have grown beyond regulation limits and therefore problems should be addressed as soon as possible. These problems can be mitigated by simultaneously protecting and improving ventilation corridors. This will require involvement of experts and government stakeholders to create a holistic approach to comprehensive urban planning and design (for streets, parks, buildings and other urban areas) which will enable better air circulation and reduction of air pollution whilst also taking into account optimisation of other benefits, including enhancing biodiversity (via green infrastructure linkages), drainage, pedestrian movement, thermal energy sources, carbon sequestration. The future urban development of Sarajevo must incorporate an environmental dimension in order to achieve sustainability in urban planning.

6. Methodology for determination of urban ventilation corridors

6.1. Physical model

The study uses the Computational Fluid Dynamics (CFD) method with time-dependent Reynolds-Average Navier-Stokes (RANS) turbulence modelling approach [27]. Navier-Stokes equations that define fluid motion in three-dimensional space, have been numerically solved resulting in 3D fields of velocity and pressure. The in-house unstructured finite-volume code 'T-Flows' [28], developed at TU Delft [33], has been used for the main computations. The code has been used for many years for Large Eddy Simulation (LES), Reynolds-Averaged Navier-Stokes (RANS) and hybrid LES/RANS solution in the research of a variety of turbulent flows and transport processes. Turbulence is modelled by the RANS k-eps-ζ-f model [34] that has been successfully tested against a number of benchmark cases and is a standard model in commercial computational fluid dynamics (CFD) codes (AVL Fire).

6.2. Considered scenarios

Two scenarios are considered, one in which air flow in Sarajevo valley is due to typical wind and one in which air movement is only due to the buoyancy force generated by temperature differences. The terrain roughness is represented by the porosity model that takes into account surface characteristics. Seven terrain zones are defined (high-rise building area, medium-rise building area, low-height private houses, forest, grass fields and parks, rivers and roads) to which different values of porosity coefficient, temperature and pollution emission are assigned. The windy day scenario considers wind along the two most frequent wind directions and at three wind intensities, assuming neutral stratification in atmosphere. The windless day scenario takes a winter's day with distinct potential temperature inversions at 300m above the ground and a gradient of 4K/km in the stable upper atmosphere, where the air flow and transport of pollutants are solely driven by thermal buoyancy effects generated by the heating from the ground. The computation of the windless day is performed in order to investigate if the same air corridors identified in the windy day scenario appear when local wind is due instead to buoyancy effects.

6.3. Computational domains

Three different computational models of terrain are used - meso, local and micro scale models. The meso-scale domain, shown in Figure 7.1, covers an area of 15 km x 13 km x 1.5 km and contains the whole Sarajevo valley including the surrounding mountains. The meso-scale computations are primarily used to identify air corridors and get a broader picture of air flow through the Sarajevo valley under the prevailing wind. Due to a large computational domain and limited computer resources, the mesh resolution is such that the impact of buildings and other human-made dominant structures on the ground could not be modelled directly as 3D objects. The influence of these objects is accounted through the roughness model that is commonly used to predict an influence of natural and human-made obstacles on the ground such as buildings, trees, etc.

The local-scale domain, shown in Figure 7.6, includes the urban part of Sarajevo (with the Old City) and covers an area of 6 km x 1.8 km x 1 km. The smaller size of the domain allows direct representation of high-rise buildings in the model. The computations on the local scale model are used to investigate the influence of high-rise buildings on air corridors and the pollution level.

The micro-scale model contains a neighbourhood in Sarajevo with a computational mesh resolution of 2-3 metres, shown in Figure 7.9. The domain is used to assess the influence of building heights on the pollution level. The computational results are used to investigate the efficiency of pollution cleaning by the incoming low-pollution wind and its correlation to building densities and heights.

7. Computational details

In the Study, the following computations were performed:

- Meso-scale computations of the Sarajevo valley
- Local-scale computations of the urban area of Sarajevo
- Micro-scale computation of Alipašin Most neighbourhood

The computations were performed by using open source T-Flows code, as developed at Delft University of Technology, and available through the GitHub platform [28]. T-Flows (which stands for Turbulent Flows) is a CFD program featuring second order accurate finite volume discretisation of incompressible Navier-Stokes equations with heat transfer and species transport. It is written in Fortran 90 and uses a Message Passing Interface (MPI) for parallel execution.

The computations provide details of the spatial and temporal evolution of flow and scalar fields over the city, in a format that can be opened and further explored by most commercial and open source CAD software.

In order to set-up computations, information on boundary conditions is needed. Information on terrain and object morphology with a resolution of 20m, as well as data on dominant objects' dimension, position and orientation is obtained from GIS software with inputs from the Office for Planning of Canton Sarajevo.

The average wind intensity and direction (wind rose), and yearly as well as hourly wind data for 2016, 2017 and 2019 at the location of Bjelave, were used to define the wind characteristics in the computations (direction and magnitude). There was limited information on ground temperature for the windless case scenario. We assumed that the temperature of roads, buildings and houses was a degree Celsius higher than the temperature of green fields and forest areas.

The air pollutant is treated as a passive scalar in all of the computations, meaning that the pollutant particles do not affect the dynamical flow field. Some of the main pollutants such as NOx, SO_2, $PM_{2.5}$, PM_5 and PM_{10} are well approximated by this approach.

Prior to simulation of air flow in Sarajevo valley, two benchmark cases, namely Gottingen Strasse, Hannover, Germany and Askervein hill, Scotland, UK were computed in order to prove reliability of adopted models and numerical methods. The Askervein hill is well-documented benchmark case frequently used for validation of CFD methods for wind computation on complex terrain. The field measurements of the Askervein Hill in Scotland had been done within the project under the auspices of the International Energy Agency. The Goettinger Strasse benchmark case is popular case used for validation of pollution concentration prediction in an urban environment. The flow and pollution measurements in a 25-metre wide, four-lane street located in city of Hannover, Germany had been conducted by the Lower Saxony State Agency for Ecology (NLÖ). Detailed description of the two benchmark cases with references, and the results of computations are reported in Appendix 1 of the report.

For future computations of the wind in Sarajevo, more detailed information on local climate will be necessary. The following information is important for the more precise definition of the boundary conditions:

- Typical duration of wind direction and intensity over different seasons
- Typical temperature of buildings, houses, roads and green fields in different weather conditions
- Characteristics of the atmospheric boundary layer (height, inversion point, temperature gradient in capping inversion layer, etc.)
- Information on emissions of air pollutants from ground sources due to household heating and traffic.

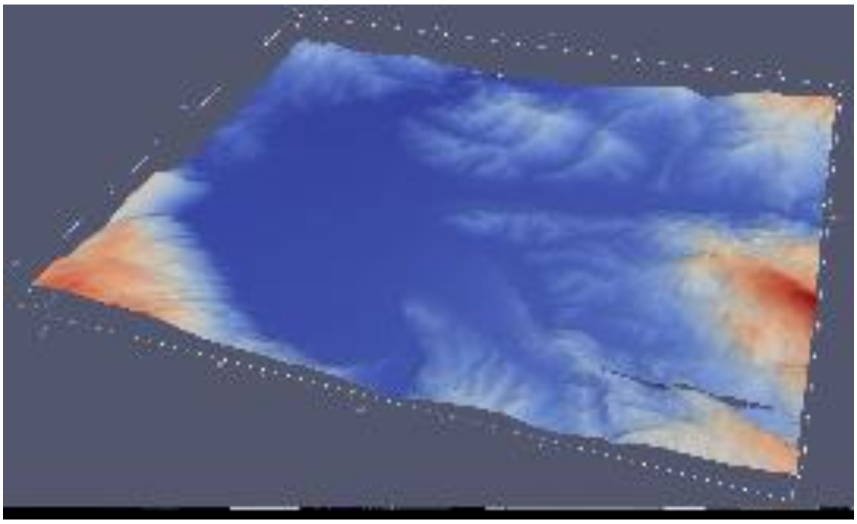
We recommend a study on microclimate to be conducted, which will provide information on weather patterns in the Sarajevo valley.

7.1. Meso-scale computations

The meso-scale computations are performed in order to identify the main air corridors through the Sarajevo valley and to analyse correlation between air corridors and level of pollution in the urban areas of Sarajevo. The computational domain, shown in Figure 7.1, covers a region of 15 km x 13 km x 1.5 km. The domain includes the Sarajevo valley together with its surroundings. It is expected that the orography of the terrain significantly influences the velocity field due to its complex and far-from-flat shape. The domain is oriented along East-West and North-South directions. The computational mesh consists of almost 8 million cells with 440 x 500 x 36 cells in x, y and z (wall-normal) directions, respectively. The mesh resolution in the urban area of Sarajevo is around 30 metres. The altitude of the ground varies from 490m above sea level, the lowest point, to 1580m, the highest point. The near-wall cells' centres are 4m above the ground on average. The top boundary is located at 2500m above sea level. The rivers that flow through the computed region, shown in Figure 7.4, are assumed to flow with a speed of 1m/s.

Figure 7.1: Satellite picture of model terrain [57]

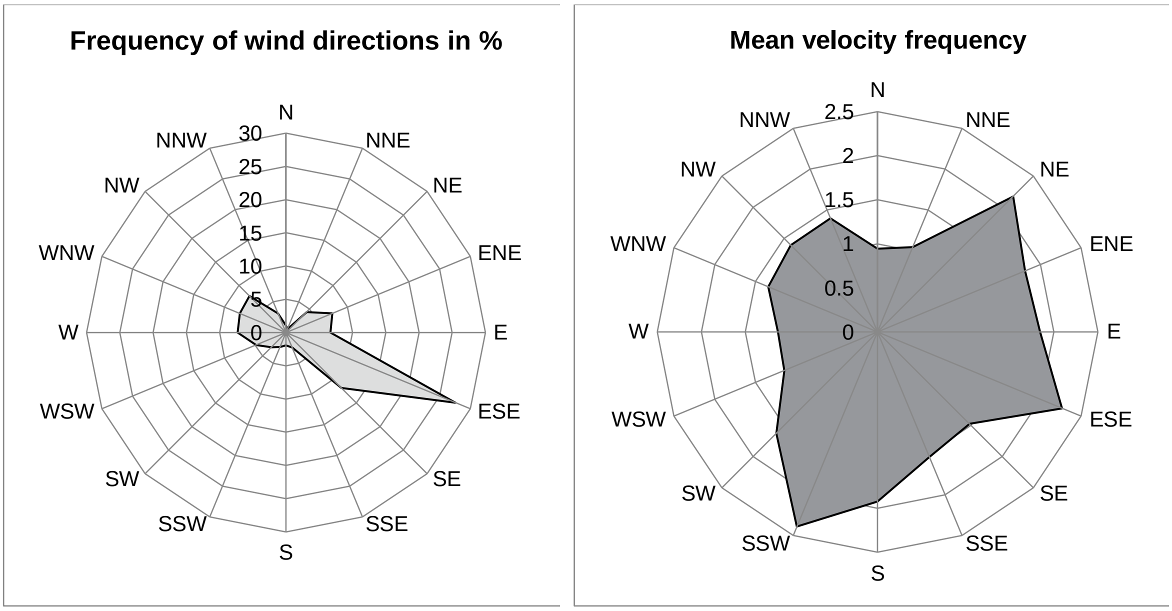
Figure 7.2 - Surface of computational domain colour-coded by terrain altitude



The meso-scale computations are performed for the two most frequent wind directions according to wind rose shown in Figure 7.3 (ESE, 120º and W, 270º) and three values of the reference wind magnitudes, 1m/s, 1.8m/s and 3m/s, as well as for the windless scenario where airflow is due to buoyancy force alone. The reference wind magnitude is velocity magnitude 10 metres above the ground for the fully developed flow over the flat plate with roughness height of 0.16m that is imposed as the inflow condition for the precursor domain. The following assumptions are made for the wind-case scenarios:

- Wind blows with constant magnitude and direction for several hours (10 hours for 1 and 1.8 m/s, and 3.5 hours for 3 m/s).
- Neutrally stratified atmospheric boundary layer is assumed where the flow dynamics is dominantly defined by a forced convection, so the buoyancy force is neglected.
- Initial condition assumes windless situation and high pollution concentration on the ground.

Figure 7.3: Wind rose for Sarajevo in 2018 according to Federal Hydro-meteorological Agency



The wall-function approach is used to treat the wall boundaries. The influence of natural (forests, rivers, grass fields) and human-made (buildings, houses, bridges, roads) obstacles on the ground are modelled by roughness model [35]. The main model parameter, the roughness height (also known as aerodynamic roughness) Zo, has been assigned different values for different terrain types following recommendation from the literature [36]. We defined seven terrain types with the corresponding values of Zo as follows:

1. Rivers, Zo = 0, smooth, moving wall with 1m/s speed
2. Buildings 40m height and higher, Zo = 5m
3. Buildings with heights between 15m – 40m, Zo = 3m
4. Private houses (up to 15 m height), Zo = 1.5m
5. Green fields, Zo = 0.16m
6. Forests, Zo = 2.3m
7. Roads, Zo = 0.5m

The roughness zones are extracted from the map by using Geographic Information System (GIS) software. Zo values are then interpolated on the computational cells near the wall, as shown in Figure 7.5.

Figure 7.4: Rivers included in the computational model

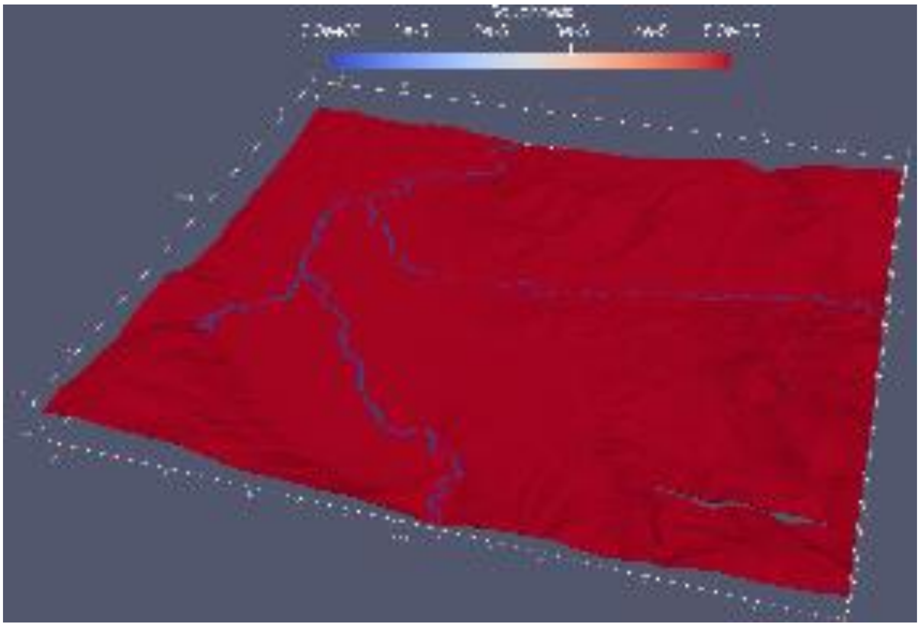
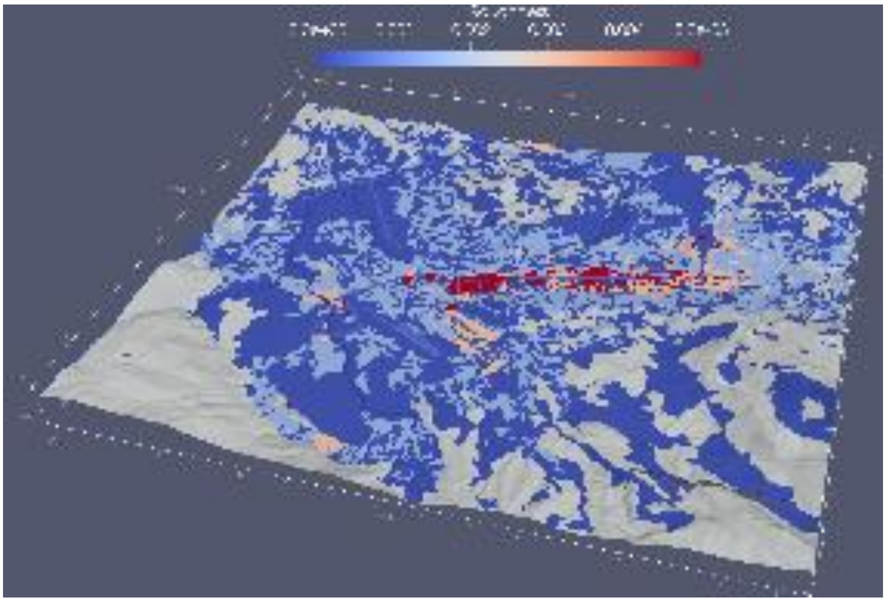


Figure 7.5 - Roughness map applied on the surface



The inflow boundary condition for the ESE wind direction case is defined with special care as the terrain where air enters the computational domain is highly irregular and far from flat. In order to generate realistic inflow condition, a precursor domain of 12km x 12km x 1.8km located 9km upstream of the inflow face of the main domain was computed. The precursor domain overlaps with the main domain for 3km. The pre-computed fully developed flow over the flat plate is imposed at the inflow boundary of the precursor domain. The velocity and turbulence fields extracted from the precursor solution are then used as the inflow condition for the meso-scale computations for the ESE wind direction case. The inflow condition for the West wind direction case is defined by using velocity and turbulence quantities profiles obtained from the pre-computed fully developed flow over the flat plate. The lateral (vertical) sides, top and outflow boundaries of both precursor and the main computational domain are treated as a constant pressure boundary condition.

The windless scenario was computed by assuming that no wind is entering the computational domain. The reference potential temperature was specified with a lapse rate of 4K/km with inversion point at 300m. We simulated a time period in which it is assumed a constant ground temperature. As the detailed spatial distribution of the ground temperature is currently not available, we assumed that the zones with objects have temperature of 1.74°C while other zones (green fields and forest) have one degree lower temperature, 0.74°C. River Miljacka is assumed to have temperature of 6°C.

Although the assumed boundary conditions are realistic, more detailed information on the main flow properties at the boundaries are needed in order to compute real case scenarios. As mentioned in the previous section, a study on urban microclimate in Sarajevo would be necessary to provide such information. Such a study would identify the main wind patterns in Sarajevo, temperature distribution on the surface level, characteristics of inversion point and mixing layer in the case of no wind, heat islands and their impact on air movement, and the influence of Miljacka on local temperature and velocity fields. Cities are conducting such studies in order to predict the impacts of the future urban development on health of its citizens, energy demand, and the traffic system (see for example [30]).

In addition to velocity and turbulence fields, we also computed transport of pollutants. As the pollutant is treated as a passive scalar, the computed concentration can be any of the usually measured components of air pollution, such as PM_5, PM_{10}, NO_x, etc. We choose to compute PM_{10} as representative of air pollution since for PM_{10} we have the most comprehensive measurements, based on which we defined the boundary and initial conditions. It is assumed that the emission of PM_{10} is due to traffic and household activities (heating). The emissions (g/s) are roughly estimated based on the available data from Canton Sarajevo but also based on some previous studies that were conducted in Canton Sarajevo. The emissions from the ground due to household activities are expressed in g/km²h (grams per square kilometre (km²) and per hour (h)), while the emission from traffic is in g/(km h). The pollution sources are kept constant throughout computation. It is assumed that the incoming wind has a low level of pollution, with value of PM_{10} equals 5µg/m³. The maximum concentration of PM_{10} is at ground level 200µg/m³ and it is decreasing as height increases. We modelled vertical distribution of PM_{10} based on the drone measurements in Sarajevo airport during the episode of high pollution in the winter of 2018 performed by Assistant Professor Dr. Adnan Mašić from the Mechanical Engineering Faculty of the University of Sarajevo (private communication).

The magnitude of pollution from different source categories is estimated based on the available data and recommendations from the literature [37], [38], [39]. The following values of pollution sources are adopted:

- Traffic source - 10g/(km h)
- Household activities from fuel combustion (charcoal and firewood) – 0.01g/(km² h)
- Residential areas heated through centralised heating units (natural gas) – 0.0001g/(km² h).

7.2. Local-scale computation

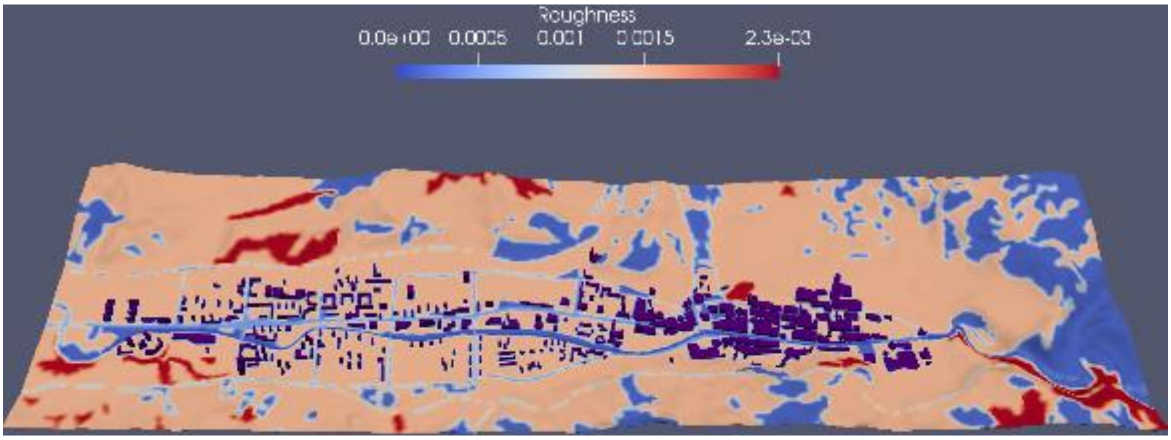
The local-scale computation is complementary to the meso-scale computation as the computational domain covers a part of the domain used in the meso-scale computation. Apart from the smaller computational domain, the main difference from the meso-scale computation is 3D modelling of the most dominant objects on the ground. This enables us to get more details on the flow dynamics such as slow separation zones and low velocity regions, as complex interplay between airflow and ground structures are directly resolved and not modelled through the roughness effect. The local-scale computation is used to determine details of the main air corridors as well as to estimate influence of tall buildings on the corridor's size and strength. Direct modelling of buildings also makes it possible to identify regions of high pollution (so called pollution traps) that are determined by the presence of flow separations caused by high buildings or natural obstacles.

The local-scale computation is performed for the most frequent wind direction (ESE, 120°) and reference wind magnitude of 1.8 m/s.

The computational domain, shown in Figure 7.6, covers a region of 6km x 1.8km x 1km and includes most of the urban region of city of Sarajevo (the old city and administrative centre in Marijin Dvor). The domain is aligned with the Sarajevo valley. The computational mesh consists of nearly 6 million cells with 440 x 500 x 36 cells in x, y and wall-normal directions, respectively. The mesh resolution in the urban area of Sarajevo is around 7 metres. The altitude of the ground varies from 490m, the lowest point, to 1580m, the highest point. The near-wall cells' centres are around 2.5m above the ground. The Miljacka river, which flows through the computed region, is assumed to flow with a speed of 1 m/s.

Figure 7.6: Satellite picture of region included in computational domain with modelled objects on the ground [58]

Figure 7.7 - Modelled objects on the ground



As it was the case in the meso-scale computation, the wall-function approach is used to treat the wall boundaries. The same roughness map, used for the meso-scale case, is also used here, see Figure 7.7. The inflow boundary condition is extracted from the meso-scale computation for the ESE wind direction case for east boundary. The lateral (south and north), top and outflow boundaries are treated as a constant pressure boundary condition.

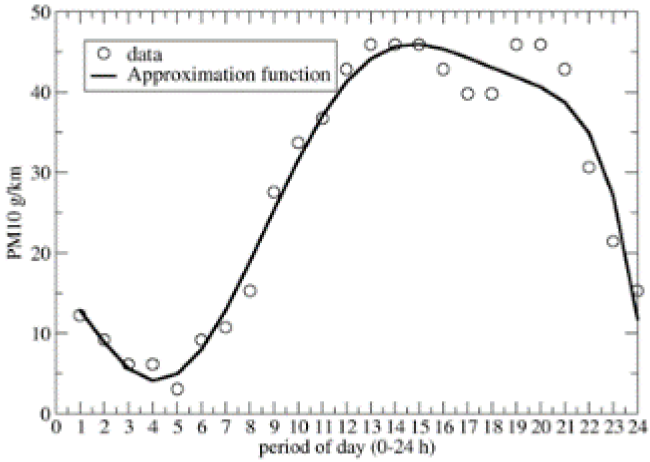
Unlike in the meso-scale computation, we modelled pollution source due to traffic as a function of time and not as a constant. The data is sourced from the report published by the Road Traffic Agency of Canton Sarajevo in 2016. The report provides data on hourly number of vehicles at several locations within the city. We took the location of Marijin Dvor as a reference location and made an approximation curve based on that data. We also assumed that 77% of all vehicles have diesel engines based on the report published by BIHAMK [31]. The main motivation for this was better mesh resolution that included 3D objects on the ground, offering more flow details such as flow separation, flow acceleration and deceleration caused by objects on the ground, and consequently more complex patterns of pollutant dispersion. The shape of the function is designed based on the collected data from the Cantonal agencies. The level of pollution due to household heating systems is modelled as a constant as the collected data indicates that there is a little variation in the source intensity for the considered period of day (from 7am till 7pm).

The following values of pollution sources are adopted:

- Household activities from fuel combustion (charcoal and firewood) – 0.01g/(km^2 h)
- Residential areas heated through centralised heating units (natural gas) – 0.0001g/(km^2 h).

As it was the case in the meso-scale, the initial value of PM_{10} set maximum concentration at ground level 200µg/m^3 and it is decreasing by increasing height.

Figure 7.8 Estimation of source power of pollutant PM_{10} based on traffic frequency at Marijin Dvor location



Source: Road Traffic Agency of Canton Sarajevo, 2016

7.3. Micro-scale computation

The computation of micro-scale location was used to analyse the influence of built asset heights on the flow field and pollution level. We chose the apartment and business complex Nova Otoka in central Sarajevo as a case study. Nova Otoka was chosen as it contains not only a mix of objects of varying size and orientation but also because of the new regulatory plan by which the existing district will be significantly changed. According to the adopted regulatory plan, Nova Otoka district is planned to be expanded both in terms of heights of the existing buildings but also with the introduction of new buildings. As shown in Figure 7.9, the existing buildings in Nova Otoka have different heights and shapes. The regulatory plan envisages construction of additional floors on some of the existing buildings, but also new buildings will be built so that the object density will considerably increase, as can be seen in Figure 7.10. For the purpose of this analysis a custom scenario was designed by two architects, Dr. Dina Šamić and Prof. Dr. Sanela Klarić. The custom design of Nova Otoka, shown in Figure 7.11, is characterised by low-height buildings orientated in the wind direction with larger areas of free space between them. This custom model is designed with aim to explore extension of air pollution reduction through lowering buildings' heights and building density.

We computed the flow through the Nova Otoka district for these three scenarios: existing buildings layout (Figure 7.9), buildings layout planned in the future (Figure 7.10); and a custom buildings layout (Figure 7.11). All computations were performed by using RANS approach in a transient mode with real time duration of one hour. The micro-scale computations were performed using an open-source CFD code "Open source Field Operation and Manipulation" (OpenFOAM). OpenFOAM is a CFD code of customised numerical solvers, and pre-/post-processing utilities for the solution of computational fluid dynamics (CFD). Turbulence is modelled by a standard k-epsilon model [40]. This model is the most widely used and validated turbulence model, with applications ranging from industrial to environmental flows.

The dimensions of the computational domains were 1000m, 560m and 365m in x, y and z direction respectively. The total number of cells was 2,427,160, with refinement in the regions where large gradients of variables are expected. The near-wall cells had a height of 1.6m, meaning that information about all of the computed variables was available at the height of 0.8m.

For all three layouts the same boundary and initial conditions were used. A constant west wind was assumed, referenced to the measured most common wind direction from the nearest meteorological station. The pre-computed fully developed flow was imposed at the inflow with a speed of 1 m/s at 25 metres from the ground. The buoyancy force was neglected.

To reduce the number of grid points in the wall-normal direction and therefore the computational costs, a wall function approach was used to define the near wall values of computed quantities. A symmetry boundary condition was used at the lateral and top boundaries. The roughness model was not used since the obstacles on the ground were modelled as 3D objects.

The initial conditions assumed concentration of pollutants being 20µg/m^3, homogeneously distributed in the whole domain and without the wind. The pollutant is treated as a passive scalar (no chemical reaction) meaning that it can represent transport of any of the most common air pollutants such as PM_{10}, $PM_{2.5}$ particles or gases like CO or NO_x. It is assumed that the incoming air has four times less pollutant (5 µg/m^3) than the stagnant air defined by the initial condition. Even pollution levels used might not be realistic for the urban environment, however the ratio of pollution level of stagnant air (defined by the initial condition) to incoming wind is the key variable for the present analysis.

Figure 7.9: Current buildings layout at Nova Otoka district [59]

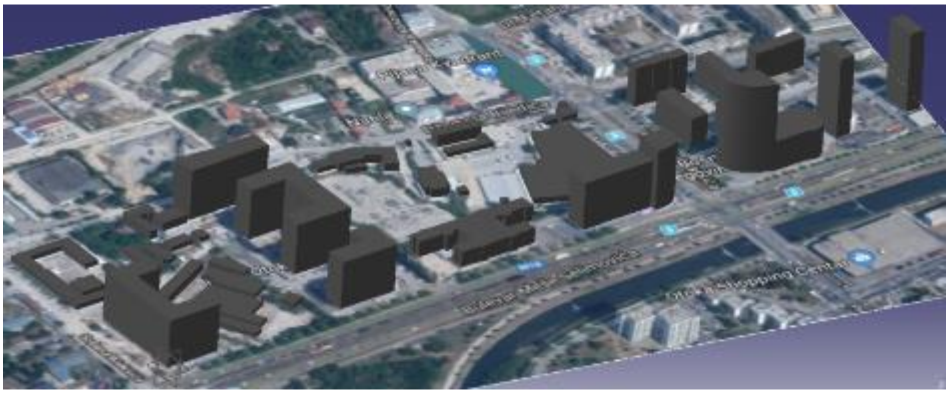


Figure 7.10 – Buildings layout planned in Nova Otoka district by the regulatory plan

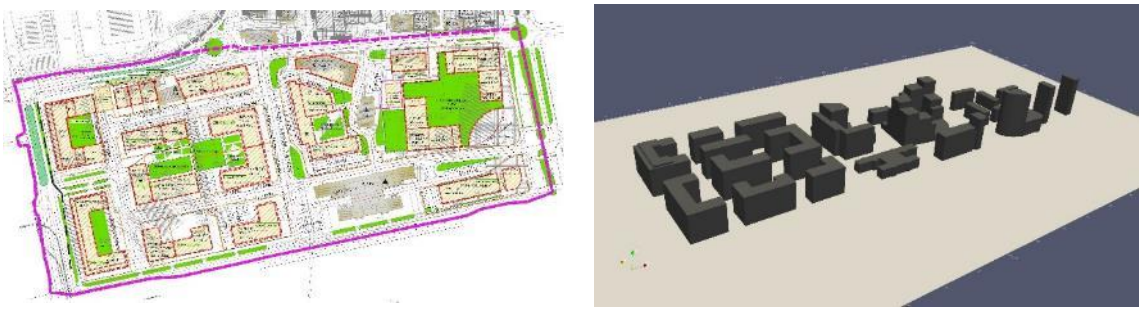
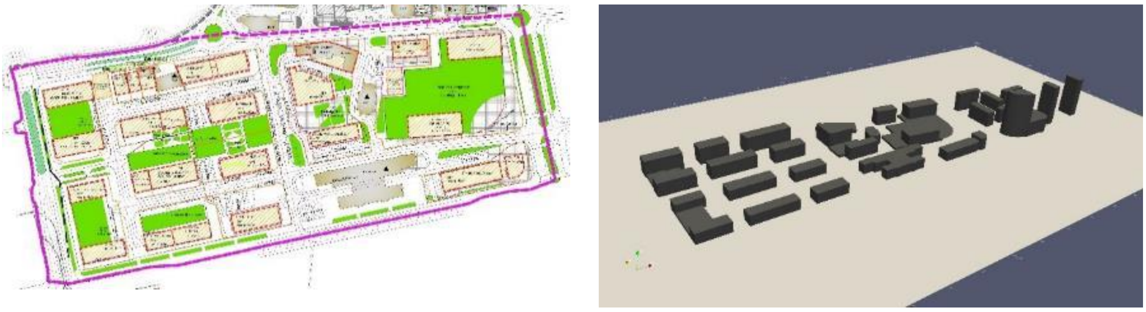


Figure 7.11 - Custom buildings layout of Nova Otoka district



8. Identification of existing air corridors and their characteristics

The air ventilation corridors are routes by which fresh air enters urban areas. The air corridors are determined both by terrain orography and ground objects (buildings, bridges, etc.) that block or channel airflow in certain directions. River canyons and channels, as well as street canyons, often determine location and shape of air corridors in cities. Good ventilation of urban areas depends on the existence of air corridors. That is why it is important to identify regions of air ventilation corridors, so that future urban development does not result in a negative impact on the existing air corridors. Furthermore, smart urban planning can enhance existing air corridors and create new ones. The air corridors are characterised by higher velocity magnitude compared to the surrounding air, therefore air corridors can be identified by analysing the velocity magnitude fields.

We first look into the results of meso-scale computations when Eastern (ESE), the most frequent, wind, is blowing. Figure 8.1 shows the velocity magnitude field 4 metres above the ground in the meso-scale domain for the case with the referent velocity of 1.8m/s. The irregular terrain orography implies a complex distribution of velocity close to the ground. The peak values in the velocity field appear in the locations of the hill tops due to mass continuity constrain, after which the airflow slows down and separates in several locations. The separation zones produce low-velocity zones in the regions downstream of the location where the flow initially separates. In addition to flow separation, the low-velocity regions are also determined by high-roughness coefficient typical for the regions classified as forest or urban areas.

Figure 8.1: Velocity magnitude field for the case with 1.8m/s reference velocity[4].

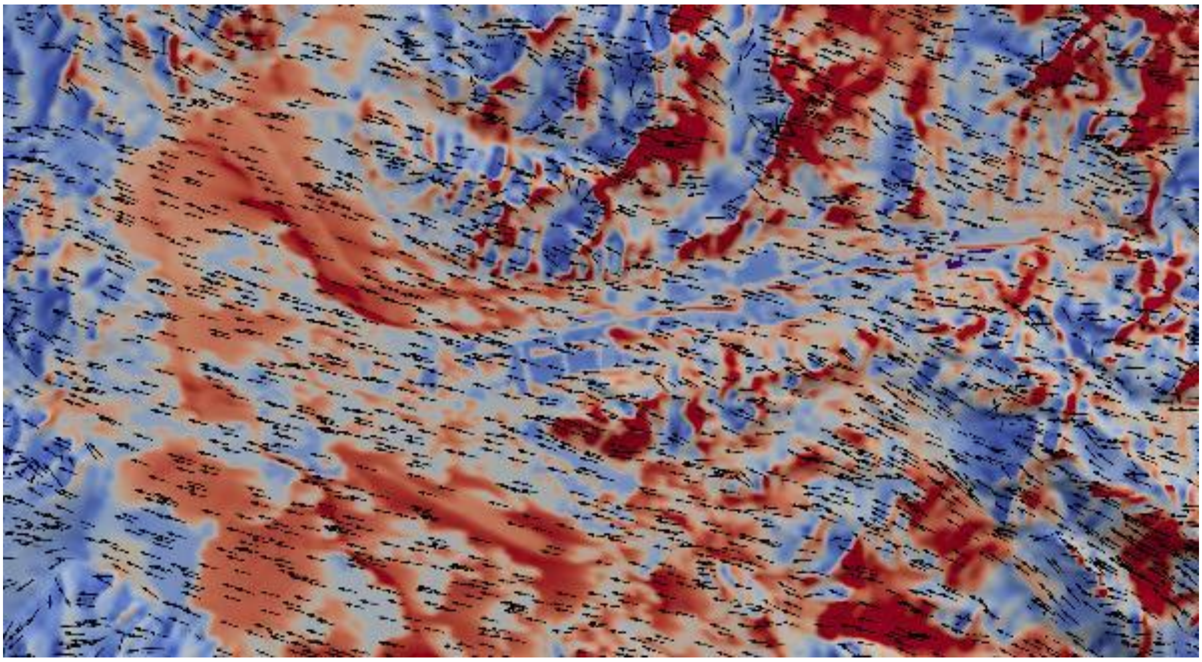


Figure 8.2 and 8.3 show the velocity magnitude fields at the surface four metres above the ground5 for the ESE wind direction and reference wind magnitudes of 1m/s and 3m/s. The separation regions identified by the vector orientation are marked by green line while yellow line is used to mark air passages from the Trebević mountains in the East into the urban parts of Sarajevo. Two separation zones occur at the lee sides of mountain Trebević hills. The air supply to the city is slowed down by

[4] Uniform vectors length is used to better visualise wind direction.

these separation zones that imply low values of velocity. The main air passages towards the city are the same for three computed reference velocities. Apart from different velocity magnitudes, the distributions of high and low velocity zones are similar for the three reference velocities.

Figure 8.2: Velocity magnitude field with corresponding vectors 1m/s reference velocity case

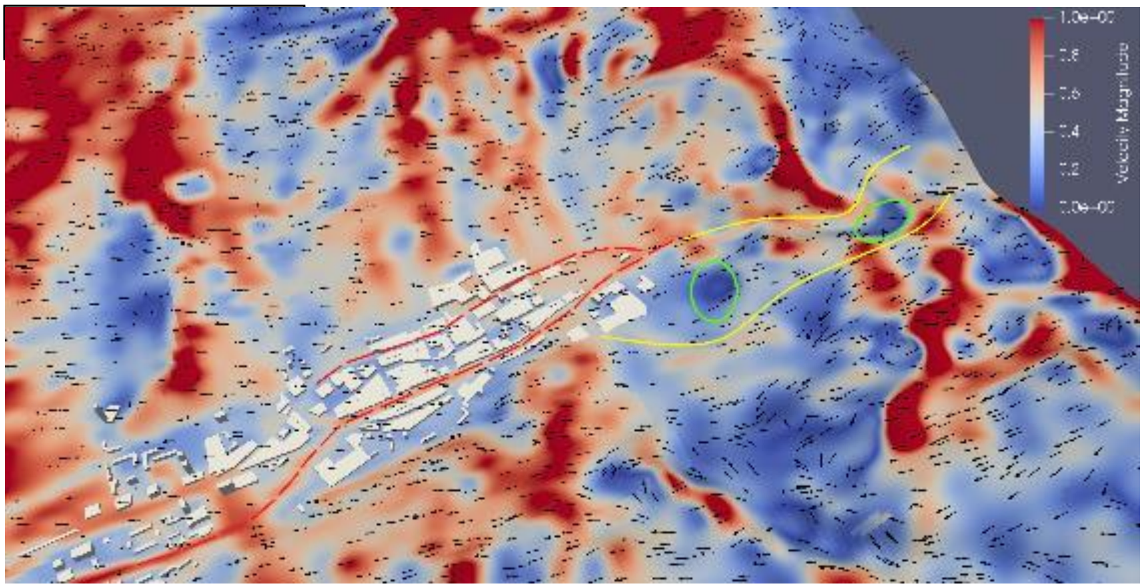
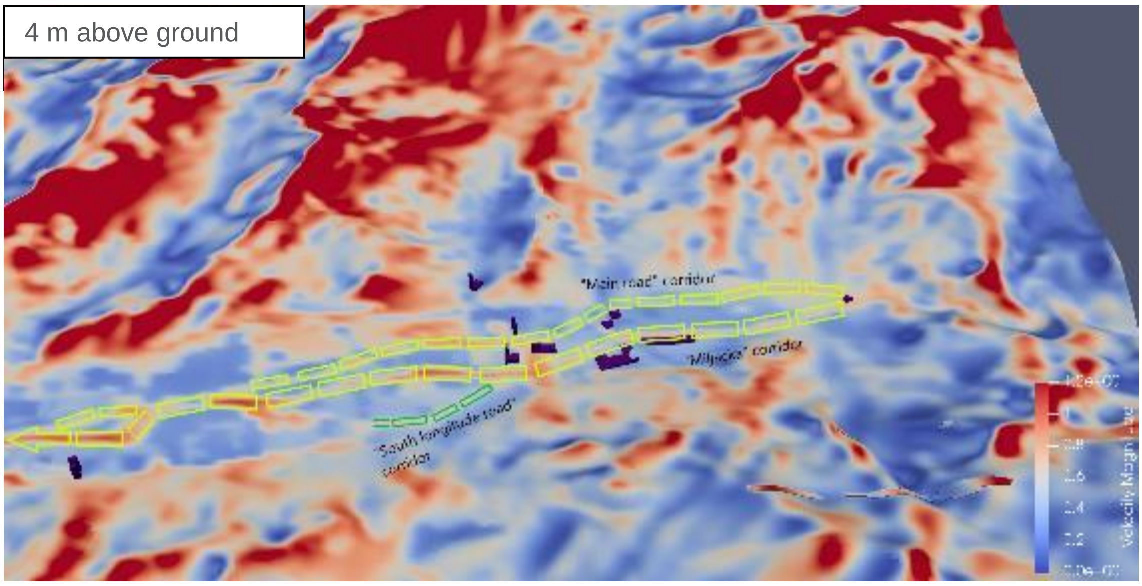


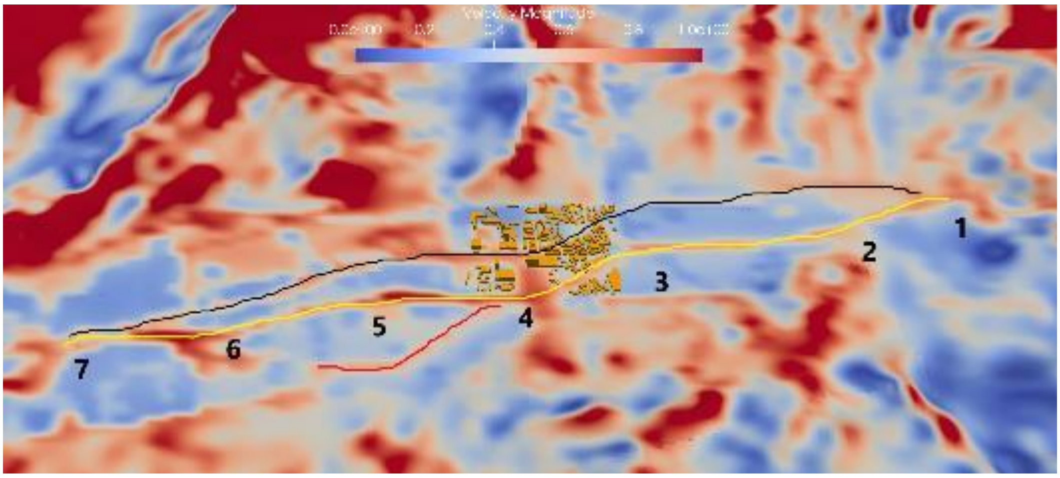
Figure 8.3: Velocity magnitude field with corresponding vectors for 1.8m/s reference velocity



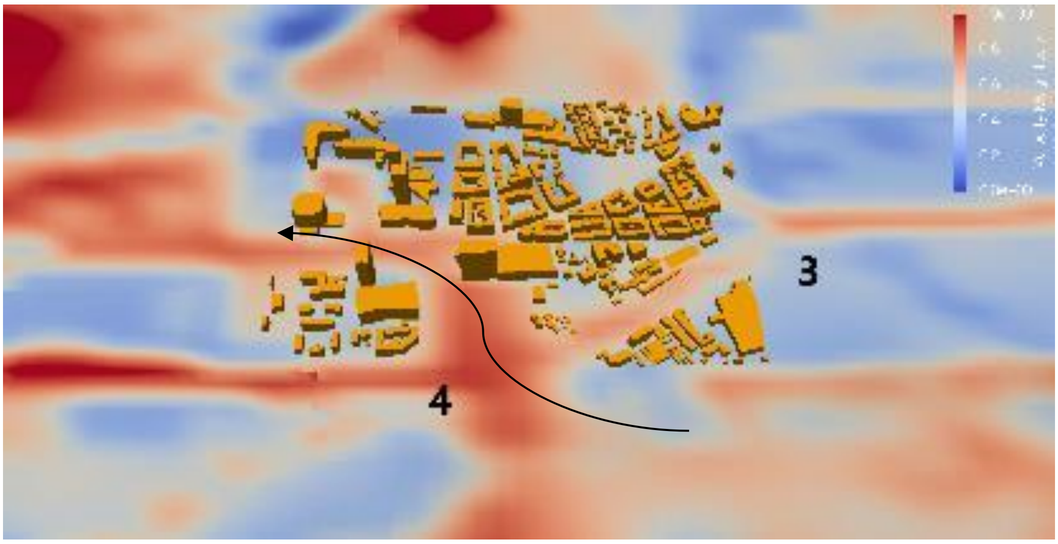
The meso-scale results indicate the existence of two main air ventilation corridors and several smaller ones. The largest air corridor, visible in the velocity magnitude field shown in Figure 8.2 is formed along the channel of Miljacka River. The velocity magnitude along the air corridor is significantly higher than the velocity magnitude outside the corridor region, and thus it significantly contributes to air ventilation in the urban areas of the city. We will refer to this air ventilation corridor as Miljacka corridor. The Miljacka corridor is formed at the location where the Miljacka River enters the city. The main air supply comes from the Miljacka canyon upstream. The width of the Miljacka corridor is approximately the same as the river channel. The intensity of airflow along the corridor is not constant but varies. The velocity magnitudes along two main air corridors at locations marked by points in Figure 8.2 and Figure 8.3 for three reference velocities shown in Figure 8.4. The minimum velocity is around 0.4m/s for the reference velocity of 1m/s while the maximum velocity is close to 1.7 m/s for the highest reference velocity of 1.8 m/s. Although the velocity magnitude varies along the corridor, it is more or less continuous from the beginning at the East to its end in the West.

We marked by numbers some characteristic locations along the Miljacka corridor in Figure 8.4. The intensity of airflow along the corridor is influenced by terrain orography and proximity of tall buildings. The segment 1-2 of the corridor is affected by the low-velocity region determined by the separation that occurs on the lee side of the Trebević hills. At point 2 the flow along the corridor gets stronger as an influx of air comes down from the hills (marked by an arrow). The velocity magnitude on segment 2-3 is more or less constant. As the river channel changes its direction at point 3, so the airflow slows down. The airflow along the air corridor splits at point 3 where one fork continues along the Miljacka channel and another one is channelled by the main road. It is interesting to notice that the velocity magnitude does not differ much for 1 m/s and 1.8 m/s at the second and third location. The proximity of hills to these locations might cause this behaviour.

Figure 8.4: Air corridors visible in velocity magnitude field from the meso-scale computation for the case with the reference velocity of 1.8 m/s.



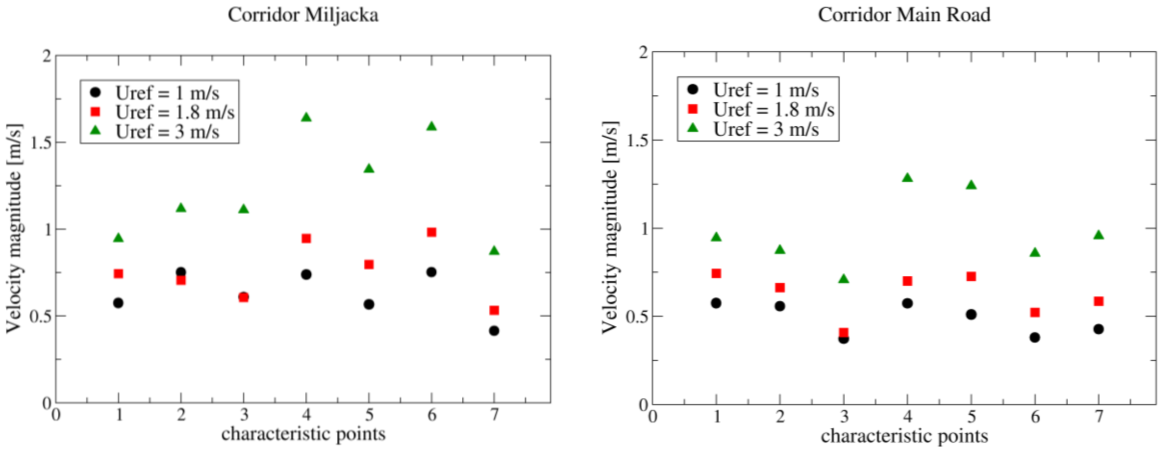
Black line – Corridor Main Road, Yellow line – Corridor Miljacka, Red line – Corridor Zagrebačka ulica



The minimum value in air velocity occurs at point 3 where the Miljacka corridor splits as it can be seen in Figure 8.5. The wind speed does not change much for the case of 1m/s reference velocity, while more differences in min and max values are present for the cases 1.8 and 3 m/s. The width of the corridor is around 75 metres on average. It is narrowest in the Dariva – Skenderija segment with 50-60 metres width due to close proximity of the buildings along the river bank. The corridor is widest in the region of Dolac Malta with a width of 100-110 metres. The location where the corridor ends when eastern wind is blowing is shown in Figure 8.4. The corridor stops following the river for a short distance at the location where the river starts to meander (Otoka district at location of the swimming pool), and then reappears close to the RTV building. As the Miljacka River enters a flat area in the west known as 'Sarajevo Field', the main corridor ceases to exist. The area of Sarajevo Field is characterised as a green field with a low value of roughness height (see Figure 8.3) which implies a higher velocity magnitude close to the ground. The corridor ends at the location of Halilovici.

The Main Road corridor is formed along the main road that heads from East to West. The computational results indicate lower intensity of airflow along the Main Road corridor compared to the Miljacka corridor, as it can be seen in Figure 8.5. This shows that the velocity magnitude is decreasing from point 1 to point 3 along the main road, which is bordered by high-density, tall buildings in the city centre. There is a sharp increase in the velocity magnitude at point 4 which corresponds to the location of Marijin Dvor district. Here the main road gets wider (four-lane street) which, together with a influx of air from the direction of river Miljacka, is the main reason for the velocity increase. We consider this location as a start of the Main Road corridor. Figure 8.4b shows connection of the corridor Miljacka to the corridor Main Road in the Marijin Dvor district. The narrow passage through which the air flows from the Miljacka corridor to the Main Road corridor seems vital for efficient air transportation through the Main Road corridor. The corridor at Marijin Dvor is around 50 metres wide and it stays approximately the same width until its end at Stupska petlja. The air flow intensity through the Main Road corridor is lower than the Miljacka corridor. The Miljacka corridor is supplied by fresh air from the wind which is mainly undisturbed by high-rise buildings at the region of Vijećnica (National Library), which is not the case for the Main Road corridor. In addition, the corridor is narrower than the Miljacka corridor with a larger number of high-rise buildings on its southern bank, reducing the air flow through the corridor. These are possible reasons for the less intense air flow through the Main Road corridor.

Figure 8.5: Distribution of velocity magnitude along two main corridors at locations marked by points for three reference velocities.



Apart from the two main corridors identified, we identified several potential local corridors which are, in general, shorter and with less capacity for air transportation than the main corridors. The potential local air corridors are the following:

- the south and north longitudinal roads which are known as "South Longitudinal" and "North Longitudinal", referred to as SL and NL further in the text. SL air corridor is visible in Figure 8.6 and it is passing through Zagrebačka, Grbavička and Zvornička streets. NL is less pronounced in the velocity field, but it has potential to be an additional air corridor due to its size and orientation (East - West);

- Alipašina Street, oriented north-south and connected to the Green Belt region, it is expected to become an air corridor when a wind blows from the south or north; and
- Two roads in Alipašino Polje - Ante Babića Street and Ive Andrića Street, which are oriented north-south and are visible in Figure 8.6.

Figure 8.6: Ends of air corridors in the western part of the city visible in velocity magnitude field from the meso-scale computation with the reference velocity of 1.8 m/s.

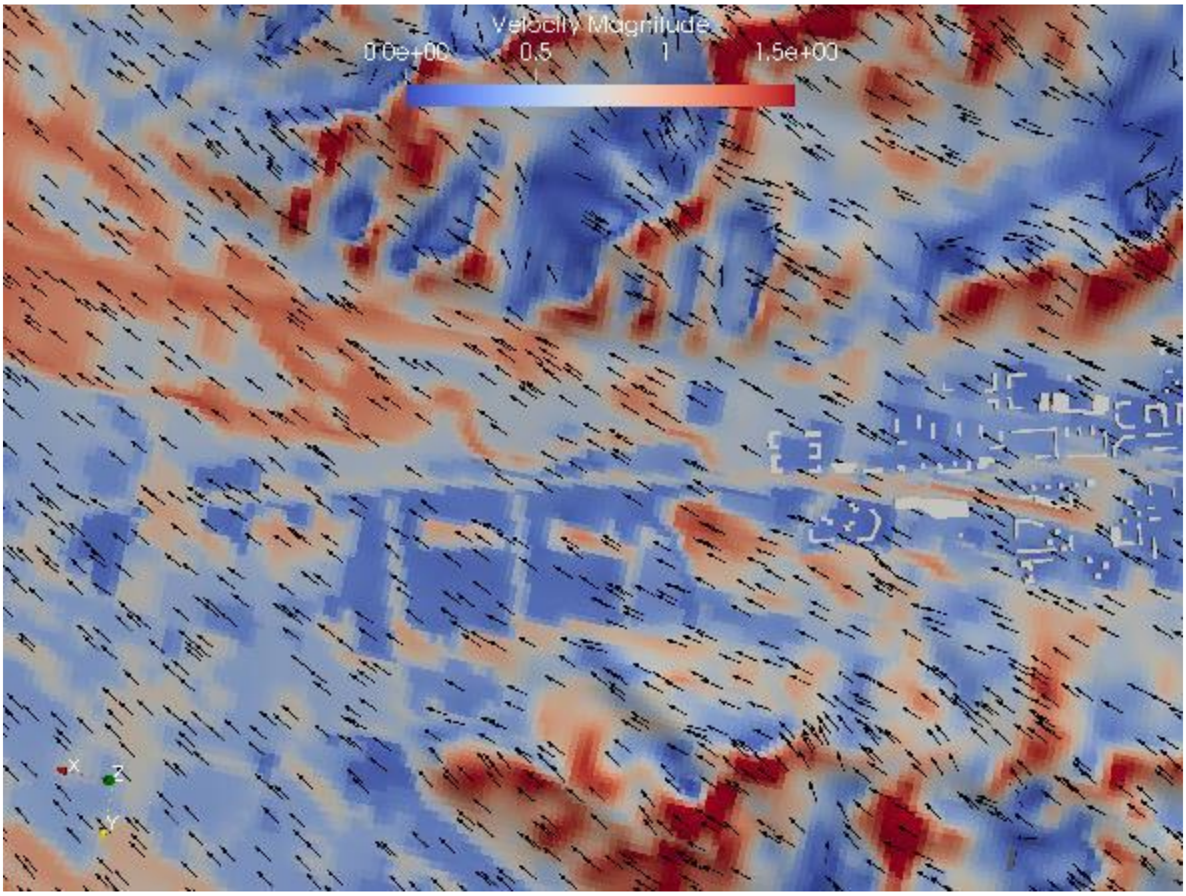
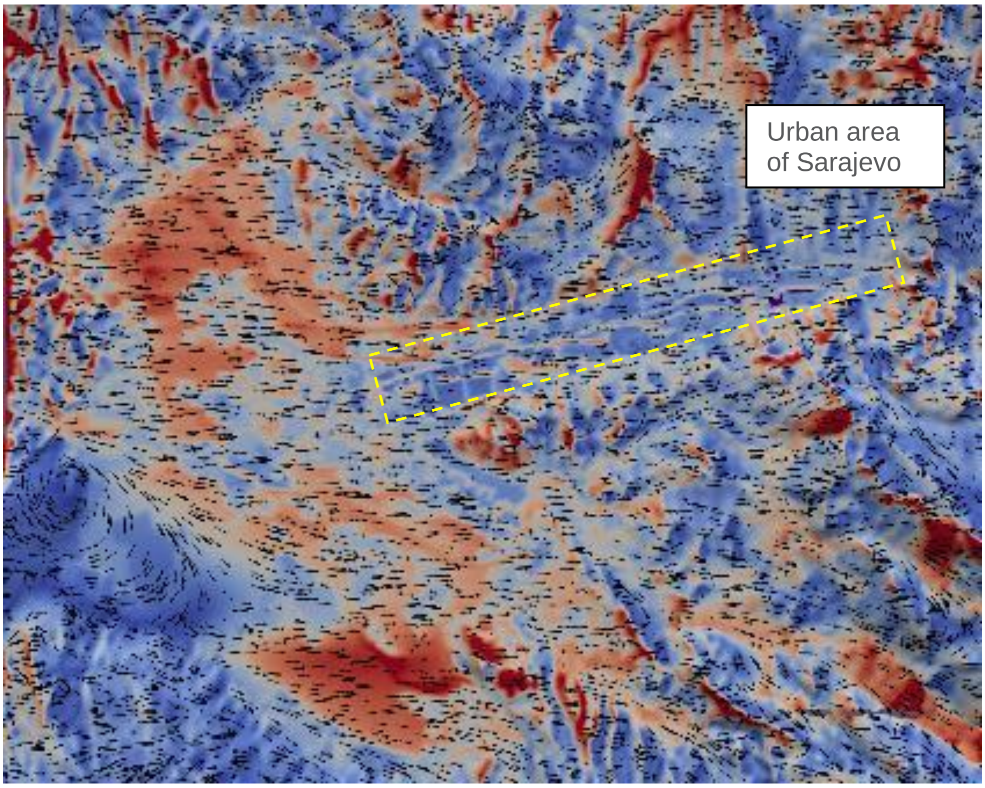


Figure 8.7 shows velocity magnitude for wind blowing from West with reference velocity of 1.8 m/s. The two main air corridors, identified in the velocity field for the wind coming from the East, are visible in the results of western wind. The Miljacka corridor has a higher intensity of air velocity than the Main Road corridor, as is the case for Eastern wind. The corridor starts approximately at the same location as it ended when the wind was modelled blowing from the east. The western wind causes a massive recirculation zone on the lee side of Igman mountain. As a result, a large area of low velocity is formed in the region of Ilidža and neighbouring settlements (Hrasnica). This has a negative effect on the efficiency of fresh air supply to this region. This particular flow pattern, determined by the terrain orography, most likely contributes to high pollution level recorded in the Ilidža region. Ilidža is the part of Canton Sarajevo with the highest number of days recording high pollution levels.

The windless case scenario was computed in order to investigate possible existence of air corridors under the sole influence of buoyancy force and no wind presence. Figure 8.8 show instantaneous velocity and temperature fields. The results reveal air movement patterns typical for a buoyancy-driven flow. The cellular patterns, visible in the instantaneous field of velocity and temperature, are imprints of thermal plumes that are generated by heating from the ground. The shape and size of these cells change over time. The plume dynamics determine intensity and direction of local air movement and transport of air pollution from the ground. The vector field, shown in Figure 8.8b, indicates that the air corridors identified in the wind-case results do not exist in windless case.

Figure 8.7: Velocity magnitude field for 1.8m/s reference velocity case and wind coming from West



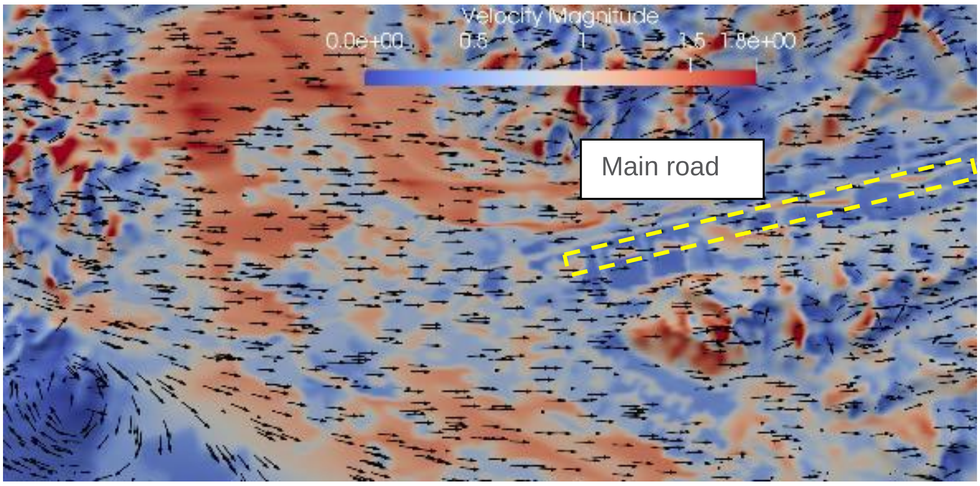
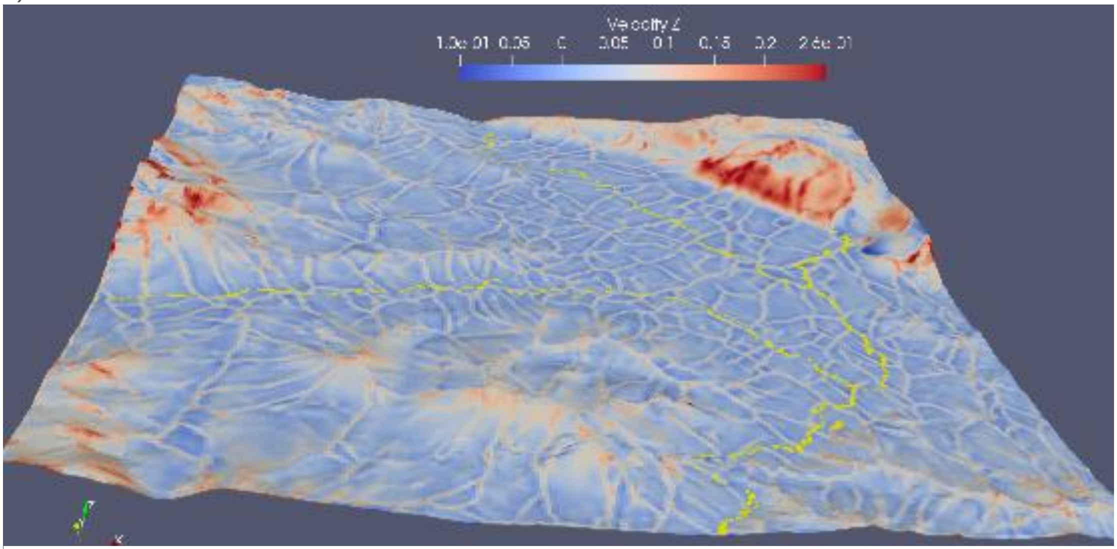


Figure 8.8c shows air flow close to the ground. As the temperature of the ground is higher than the temperature of the air, air heated from below is lifted due to lower density. The flow is organised in plume structures. The pollutant dispersion in the Sarajevo valley under windless conditions and temperature inversion point at 300 m is visible in Figure 8.8c. Temperature inversion is natural phenomenon in which layer of air close to the ground has lower temperature than the air layer on top of it. Under normal conditions air temperature usually decreases with height. The temperature

inversion point is the point where the temperature starts to rise at some distance from the ground. The low temperature inversion point, as simulated here, implies a narrow layer of air in which some air flow is possible. This condition leads to very high pollutant concentration due to limited ability of air to transport pollutants and disperse them into the atmosphere. Even though the stable stratification condition and its implications on the pollution level are very important for understanding the problem of pollution in Sarajevo, more detailed analysis of this case is outside of the scope of the present study. We recommend this case to be included in future studies of pollution in Sarajevo.

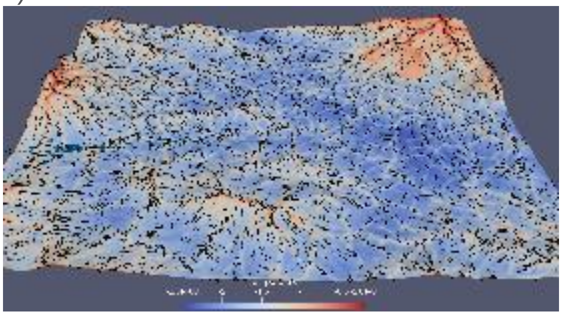
Figure 8.8: Instantaneous z-velocity field (a), temperature field with vectors on ground (b) and (c) z-velocity field in vertical plane cut through urban area for windless scenario.

a)



Yellow line represents location of rivers in the computational domain

b)



c)

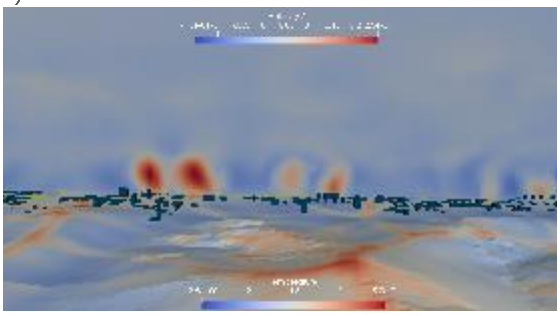
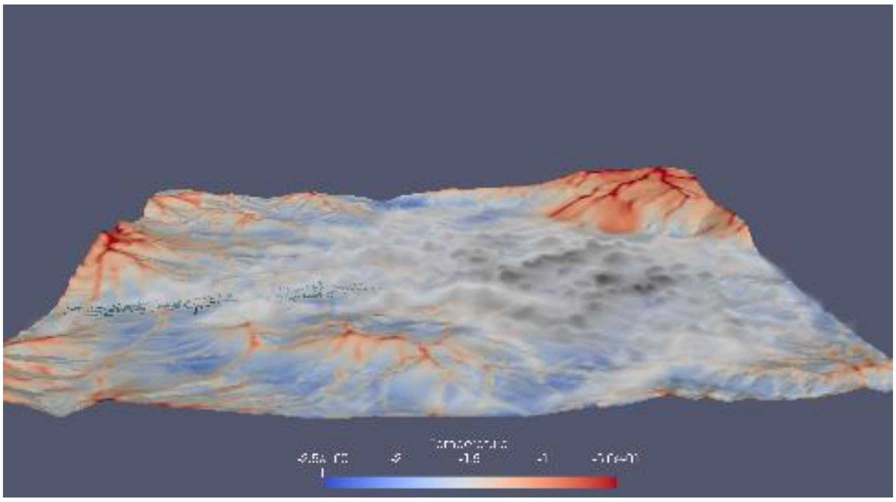


Figure 8.9: Volume rendering of pollutant concentration in Sarajevo's valley

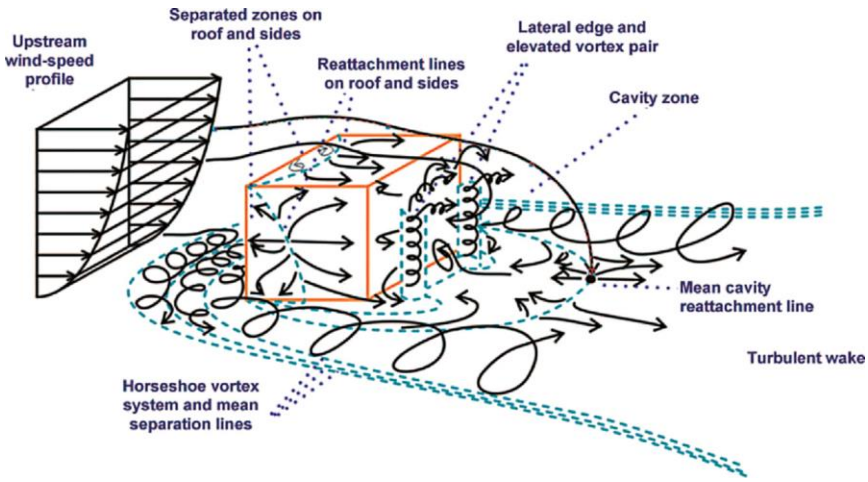


In order to protect the air corridors in Sarajevo we recommend formal recognition these air corridors. The regions that are declared as an Air Corridor Zone should be protected from high-rise buildings. Furthermore, we recommend making CFD analysis obligatory for all future regulatory plans in Sarajevo. CFD analysis should confirm that future objects will not result in a major impact on the air corridors in terms of supply of fresh air. In addition, CFD analysis should also prove that new objects will not significantly increase pollution in the region. In order to clearly define the scope and objectives of CFD analysis of regulatory plans, it would be necessary that Canton Sarajevo makes its own standard on urban ventilation and impact of new buildings on the pollution level.

9. Impacts of tall buildings on air corridors and pollution level

The layout of buildings in relation to one another can have a significant impact on the air corridors. Buildings can both enhance and suppress air ventilation in urban environment depending on building size, form and orientation relative to wind direction, position of neighbouring buildings and flow parameters such as Reynolds number. Because of the non-linear nature of turbulence, it is difficult to know a priori what kind of impact different urban forms will have on air ventilation. The flow around a single building is well studied and understood ([41] among others), but the flow dynamics can be completely changed when a group of buildings is present due to the complex interaction of flow with solid boundaries. Figure 9.1 shows a flow pattern around single isolated building. The main impact of a single building on air flow is formation of a separation bubble behind the building (the wake), whose size and shape depend on geometry of building and flow parameters such as incoming air velocity. As a result of a building presence, flow slows down downstream of the building reducing transport of the fresh air. The high-pressure region is formed in front of the building (so called stagnation region) while a low-pressure zone is generated in the wake. The flow pattern shown in Figure 9.1 can significantly differ in cases where air is flowing around group of buildings. For example, a downward drift behind the building can be significant, effectively enhancing air flow and mixing in the wake. The recent studies confirm that high-rise buildings make negative impact on air ventilation and pollution level ([42], [33], [30], among others) [30] has demonstrated that changing the height of a single building placed in a group of buildings can lead to increase of pollution levels on-site, while a study on the microclimate of London, conducted by [42], concluded that high-rise buildings are in general reducing the wind permeability and decreasing the wind potential in the urban area due to sheltering effects.

Figure 9.1 Schematic representation of the flow dynamics of flow around single low-rise building (Source: From [43] and modified by [44])



The main parameter that determines the level of impact of a building on surrounding air flow is a reattachment length that usually coincides with length of the recirculation bubble. The size of the recirculation bubble is difficult to predict a priori as many parameters influence it such as velocity of incoming air, size and shape of the building and the relative position of other neighbouring buildings. However, the empirical correlation proves to be useful in approximating the recirculation length, at least when a single building is under consideration. [33] proposed the following correlation for the recirculation length:

$$L_R = \frac{AW_C}{1+BW_C/H} \tag{9.1}$$

Where H, W_C and L are height, cross-wind width and along-wind length of the building with

$A = 1.8(L/H)^{-0.3}$ and $B = 0.24$. If $L/H < 0.3$ then $A = 2.58$ and if $L/H > 3.0$ then $A = 1.3$.

It appears that the recirculation length of a typical building falls within the following range 0.7H to 3H. This is an important parameter for deciding measures for protection of air corridors.

We look into the results of the local scale computations in order to analyse an impact of buildings on the two main air corridors. Figure 9.2 shows velocity magnitude field with streamlines at the location where the Miljacka corridors starts. The main route by which air is supplied to the corridor is along a narrow path between Vijećnica (National library) on right and a group of objects on left. The air is channelled through the corridor further downstream by the buildings aligned with Miljacka River. The large recirculation zone, identified in the meso-scale results, is visible in the streamlines at the lee side of Trebević hills. The air supply to the Miljacka corridor from the direction of Trebević Mountain is slowed down by the separation region, but also by buildings that act as obstacles to the incoming wind. However, the air passage, marked by an arrow in the figure, is present between two buildings supplying an additional flow to the corridor. The figure reveals a weak wind through the narrow streets formed by the buildings in the central part of the figure. The corridor supplies the air to the central part of the city through the side streets (marked by arrows).

Figure 9.2: Velocity magnitude field at the eastern part of Sarajevo for 1.8m/s reference velocity

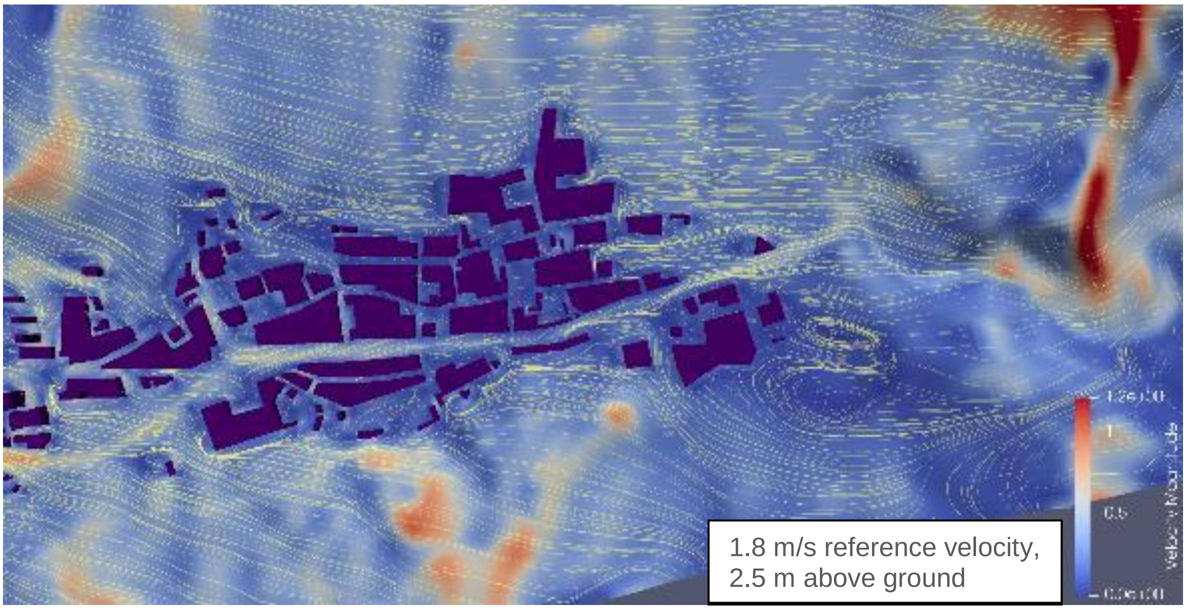


Figure 9.3 shows further development of the Miljacka corridor and formation of the Main Road corridor in Marijin Dvor. Here we can see how the proximity of buildings influences airflow through the corridors. The velocity magnitude along the Miljacka corridor varies mainly due to the impact of the buildings located upstream of the wind. The Main Road corridor is much more affected by high-rise buildings due to proximity of such objects to the location of the corridor. The streamlines along the Main Road corridor indicate highly irregular flow, interrupted by numerous recirculation zones which slow down airflow along this corridor. The presence of high-rise buildings upstream of the corridors causes a lower intensity of airflow through the Main Road corridor. This is visible in Figure 9.4 in the location of a group of 4 tall buildings, marked on the figure, which cause a low velocity zone that slows down air transport along the Main Road corridor. Further downstream a low-level building, marked on the figure, does not have a negative impact on the air corridor as its height is not sufficient for creating large separation zone. We can conclude that the local-scale results confirm without any doubt that the high-rise buildings can have a significant impact on the airflow through the corridors. The results imply that these buildings, at least 30 metres in height and located on the south side of the corridor, are likely to have a negative impact on air flow through the corridor.

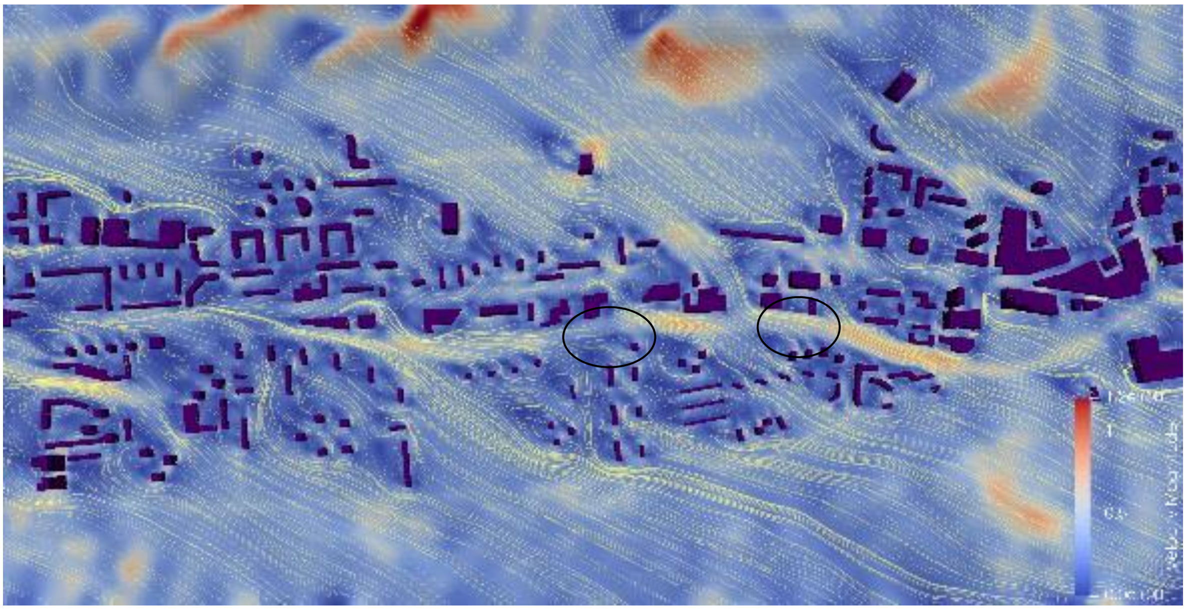


Figure 9.3: Velocity magnitude field in Miljacka corridor and formation of Main Road corridor

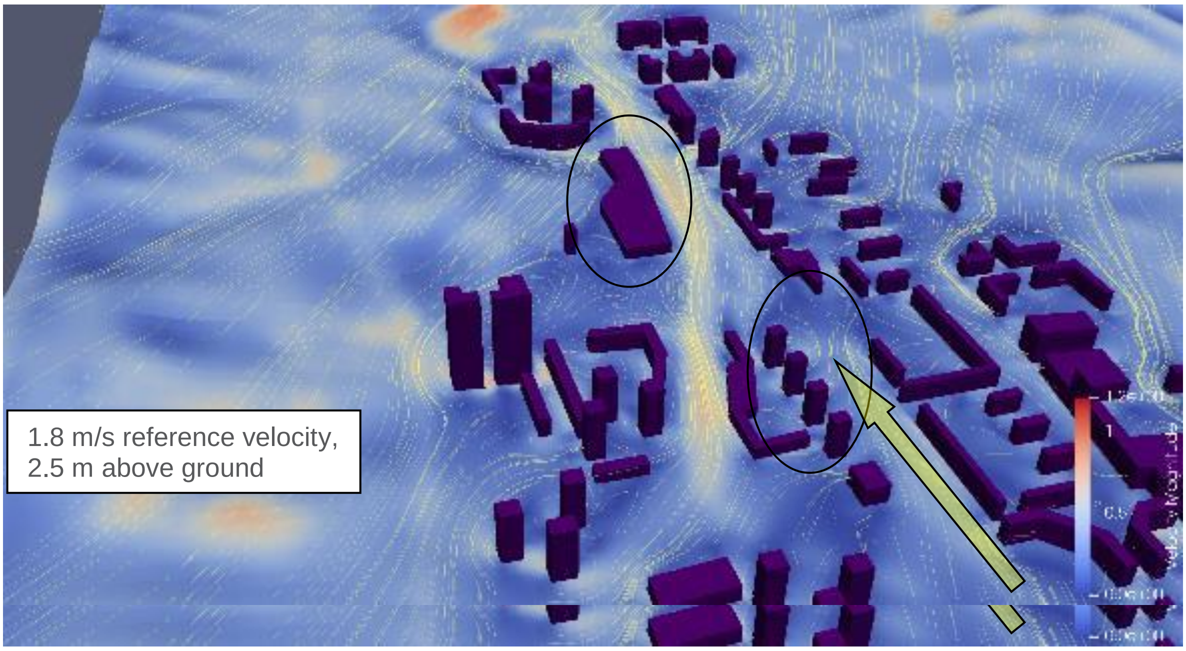


Figure 9.4: Velocity magnitude field around four tall buildings in Main Road corridor

An influence of building heights on the pollution level is investigated by computation of micro location at Alipašin Most, part of the Nova Otoka district in the central part of Sarajevo. We looked at the efficiency of pollution cleaning by the incoming low-pollution wind and its correlation to buildings' layout. Three computational domains, shown in Figure 9.5 to Figure 9.7, were considered: a) the present buildings layout; b) the regulatory plan buildings layout; c) a custom layout designed for the purpose of this study. The regulatory plan envisages a significant increase in the building heights and density. The initial condition assumes a windless situation with air pollution (20 μg/m^3) that is homogeneously distributed across the domain. No source of pollution is considered in these computations.

Figure 9.4-9.7 show the instantaneous velocity field for three models considered one hour after the wind starts. The flow organisation in these three cases is very different, due to significantly different disposition of objects and difference in objects' heights. Strong separation zones are formed in the wake of the large objects while high velocity flow streams are present in the narrow spaces between the buildings. It can be observed that the low velocity region formed close to the outflow boundary is more pronounced for the tall buildings' domain (see Figure 9.6) compared to the other two domains. The custom layout, shown in Figure 9.7, has more homogeneously distributed velocity magnitude, with less pronounced difference between the extreme values of velocity.

Figure 9.5: Top view (left) and side view with cut plane at y=102 m (right) of instantaneous velocity field for present buildings layout

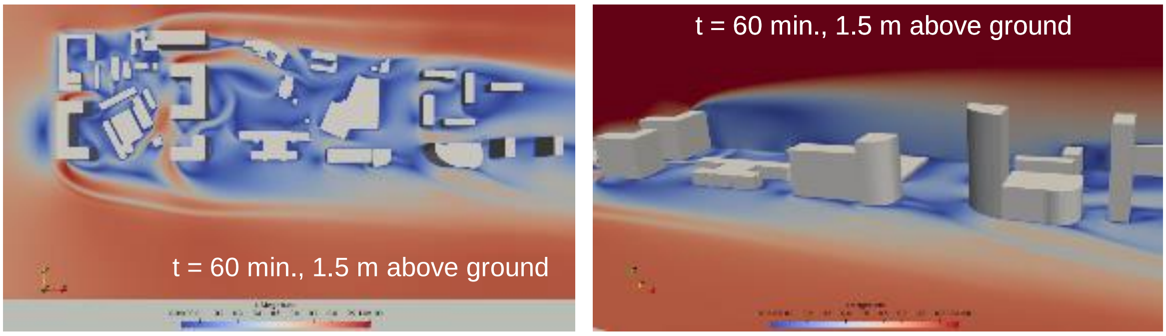


Figure 9.6 - Top view (left) and side view with cut plane at y=102 m (right) of instantaneous velocity field for regulatory plan buildings layout

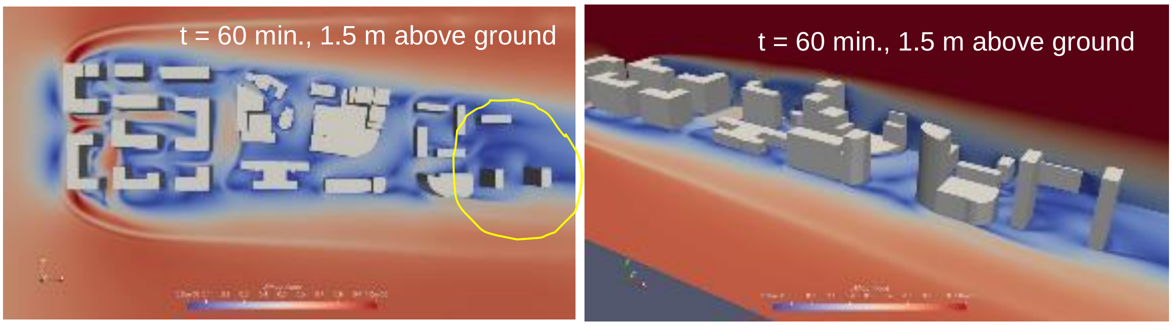


Figure 9.7 – Top view (left) and side view with cut plane at y=102 m (right) of instantaneous velocity field for custom buidlings layout

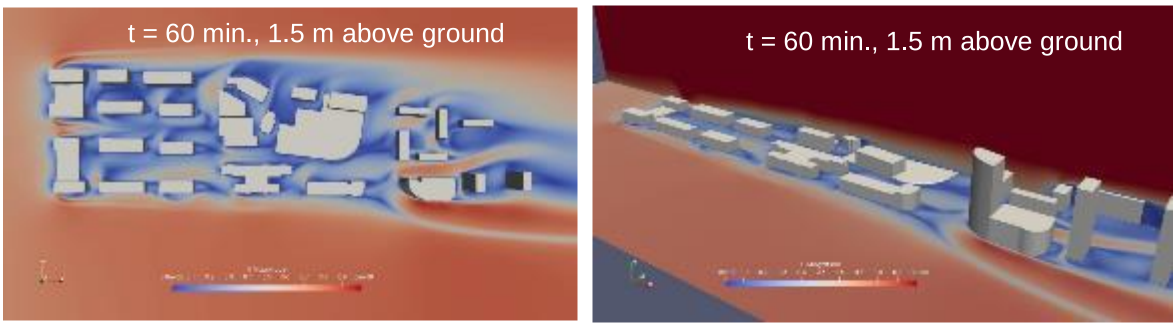


Figure 9.8 to Figure 9.10 show the pollution field in the three cases at two time instances: after 30 and 60 minutes. The incoming wind is less efficient in flushing the air pollution for the regulatory plan layout, characterised by more dense and tall buildings, compared to the other two cases. The best result is obtained for the custom layout, which is efficiently flushed of the pollutants after one hour, while the tall buildings domain has pockets of high pollution even after one hour of wind. The full impact of the modified velocity field on the pollution level is seen in Figure 9.11 and Figure 9.12. The main reason for the less efficient flushing of pollution for the second domain is the appearance of strong re-circulation zones in the wake of the tall buildings, shown in Figure 9.13 and Figure 9.14. The recirculation zones slow down airflow and trap the pollutant in the recirculation zones. The zones of high pollution appear to be very persistent over time. These results confirm the assumption about the negative effect of building height on the air quality downstream of their location.

Figure 9.8: Instantaneous pollution field at two time instances in the present buildings layout

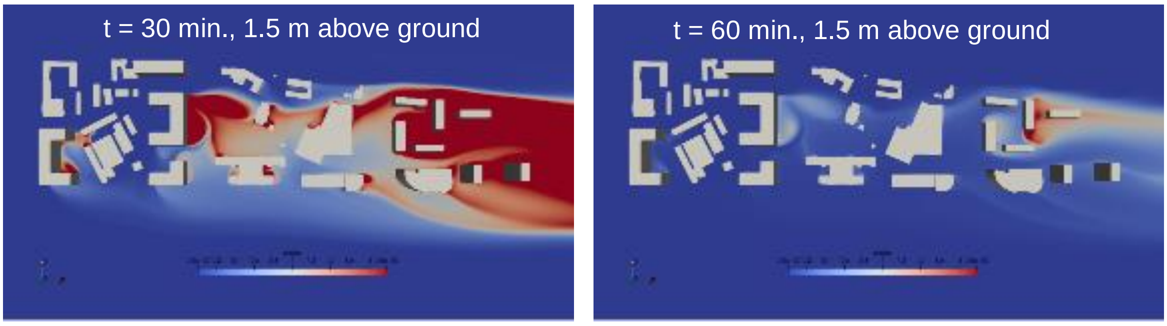


Figure 9.9 - Instantaneous pollution field at two time instances in the regulatory plan buildings layout

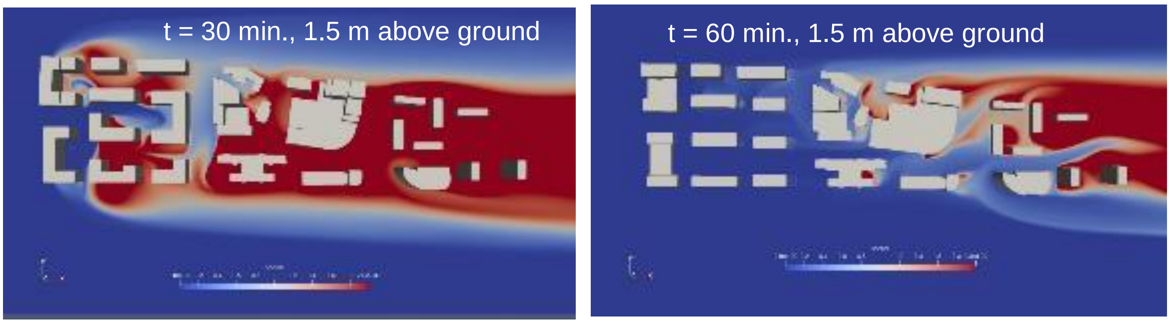


Figure 9.10 - Instantaneous pollution field at two time instances in the custom buildings layout

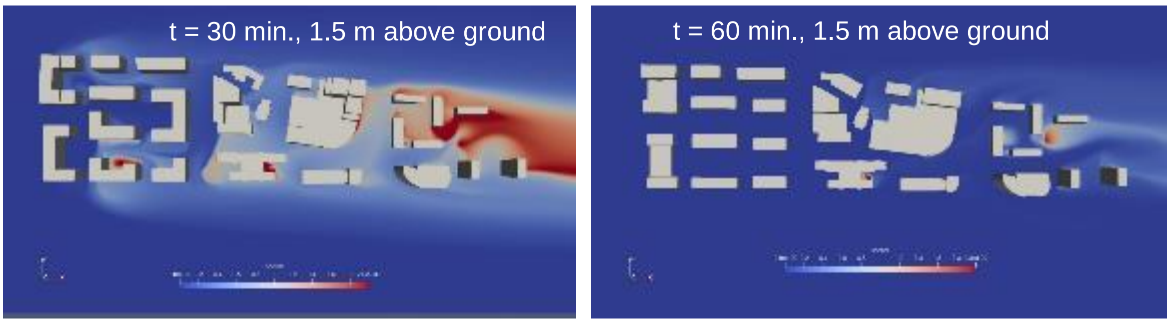


Figure 9.11: Iso-surface of instantaneous pollutant concentration for present buildings layout

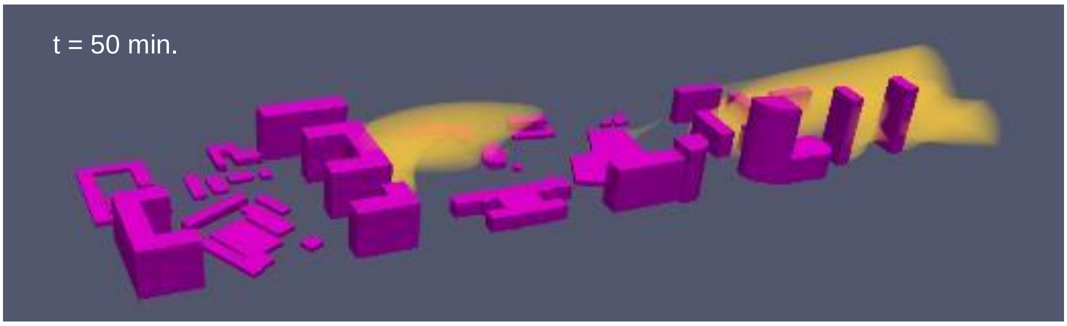


Figure 9.12: Iso-surface of instantaneous pollutant concentration for regulatory plan buildings layout

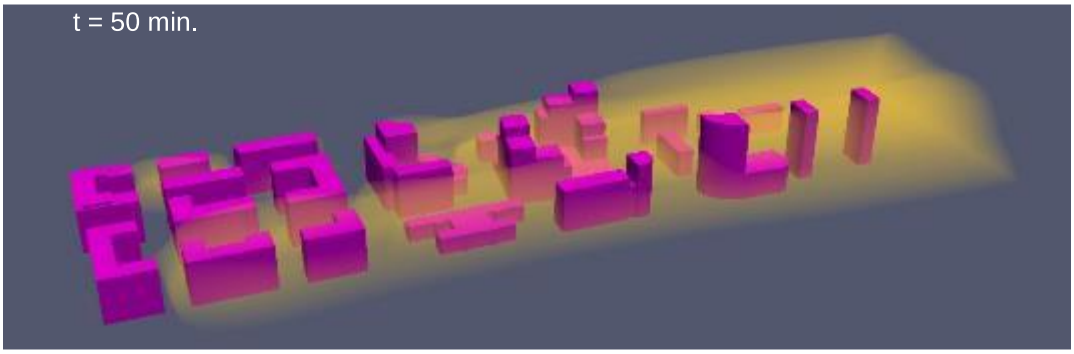


Figure 9.13: Instantaneous field of pollutant in vertical plain for present buildings layout

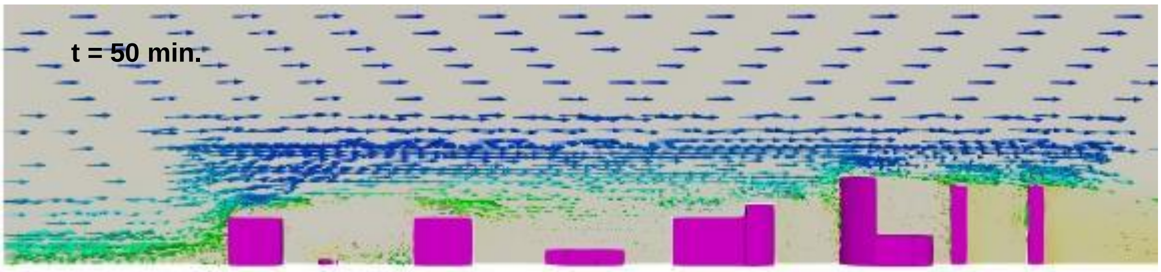
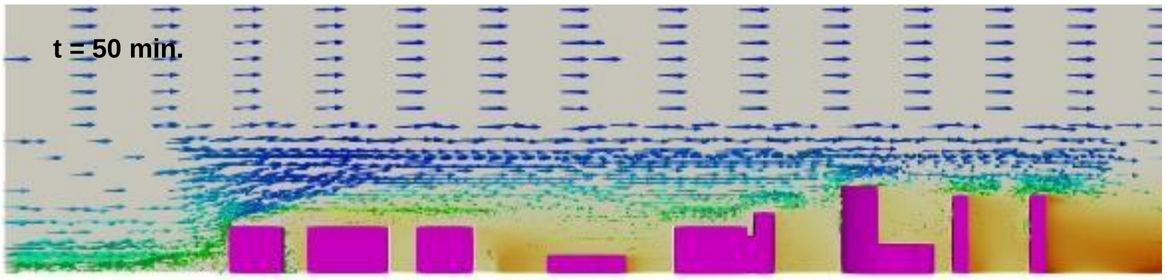


Figure 9.14: Instantaneous field of pollutant in the plain for regulatory plan buildings layout



It is confirmed that the high-rise buildings located along the Main Road corridor are slowing down air along the corridor and make it less efficient in transportation of fresh air flowing in from the east. Intensity of air flow along the main air corridors is not constant but varies, depending on the layout of the buildings in the vicinity of the corridors.

10. Conclusions and recommendations

The computations of wind in the Sarajevo valley identified two main air ventilation corridors, named after their topographical features, the Miljacka corridor and the Main Road corridor. Both air corridors are roughly oriented east-west.

The air corridor Miljacka is determined by the Miljacka river channel. It stretches from the east, where the Miljacka enters the city (at Bentbaša) until the location where the meandering of the river starts in Sarajevo's Field at Halilovici. The corridor width varies due to differing proximity of buildings along the channel. The maximum width is around 110 metres at location of Dolac Malta and the minimum width is around 60 metres in the segment Vijećnica – Skenderija. The wind intensity along the corridor also varies both in time and space, influenced by the complex interaction of air flow and the objects in the corridor's vicinity.

The air corridor Main Road is formed along the main road that connects eastern and western parts of the city. The corridor stretches from Marijin Dvor in east and ends at location of Stupska Petlja in the west. The width of the corridor is almost constant, at around 50m wide. The air flow is more intense along Miljacka air corridor with several possible explanations, such as undisturbed supply of air at Vijećnica, the larger width of the Miljacka corridor and fewer high-rise buildings on the southern edge of the Miljacka corridor compared to the Main Road corridor.

The presence of high-rise building in the corridor vicinity reduces wind permeability, thus reducing the supply of fresh air to the corridors. In addition, the recirculation zones in the wakes of buildings slow down air flow through the corridors if the wakes penetrate into the corridors. Therefore, it is important to protect existing routes by which the air is supplied to the corridors, as well as to prevent any negative influence from new buildings on the air flow through the corridors. Based on the empirical formula for the recirculation length proposed by [33] we estimate that 20m buildings' height would not cause a negative impact on the air flow through the corridors. Accordingly, we propose restricting buildings' heights to 20m, across a ~200m wide belt on each side of the main air corridors. This will ensure that new buildings do not produce recirculation zones long enough to disrupt with air flow in the corridor.

Apart from these two main corridors, additional local air corridors are identified. These are much shorter than the main corridors, but can play important role in supplying fresh air into the city. These corridors are the South Longitudinal corridor (which coincides with the South Longitudinal road that is defined by the following streets: Zagrebačka, Grbavička and Zvornička), North Longitudinal road, Alipašina Street (that lays in the Green Belt), Ante Babića Street and Ive Andrića Street (both in Alipašino Polje district).

Built-up coefficients inside the urban area of Sarajevo in certain zones grew beyond regulation limits and therefore problems should be addressed as soon as possible. These problems can be mitigated simultaneously by protecting and improving ventilation corridors. This can be done with the involvement of experts and government stakeholders to create a holistic approach to comprehensive urban planning and designing (for streets, parks, buildings and other urban areas) which will enable better air circulation and the reduction of air pollution. Future urban development of Sarajevo must incorporate an environmental dimension in order to achieve sustainability in urban planning.

The results of the micro-scale computations clearly demonstrate the importance of three-dimensional modelling of air flow and pollutant dispersion within an urban environment prior to new building constructions involving high-rise buildings. As is seen from the results, changing building position, orientation and height, can have significant effects on air quality on-site. That is why it is important to assess the impact of new construction by using complex modelling (CFD or wind tunnel). This would help in designing a more sustainable and healthier urban environment.

In order to protect the air ventilation corridors in Sarajevo we recommend several measures. In Sarajevo Canton, primary and secondary ventilation corridors are identified (see Figure 10.1), namely:

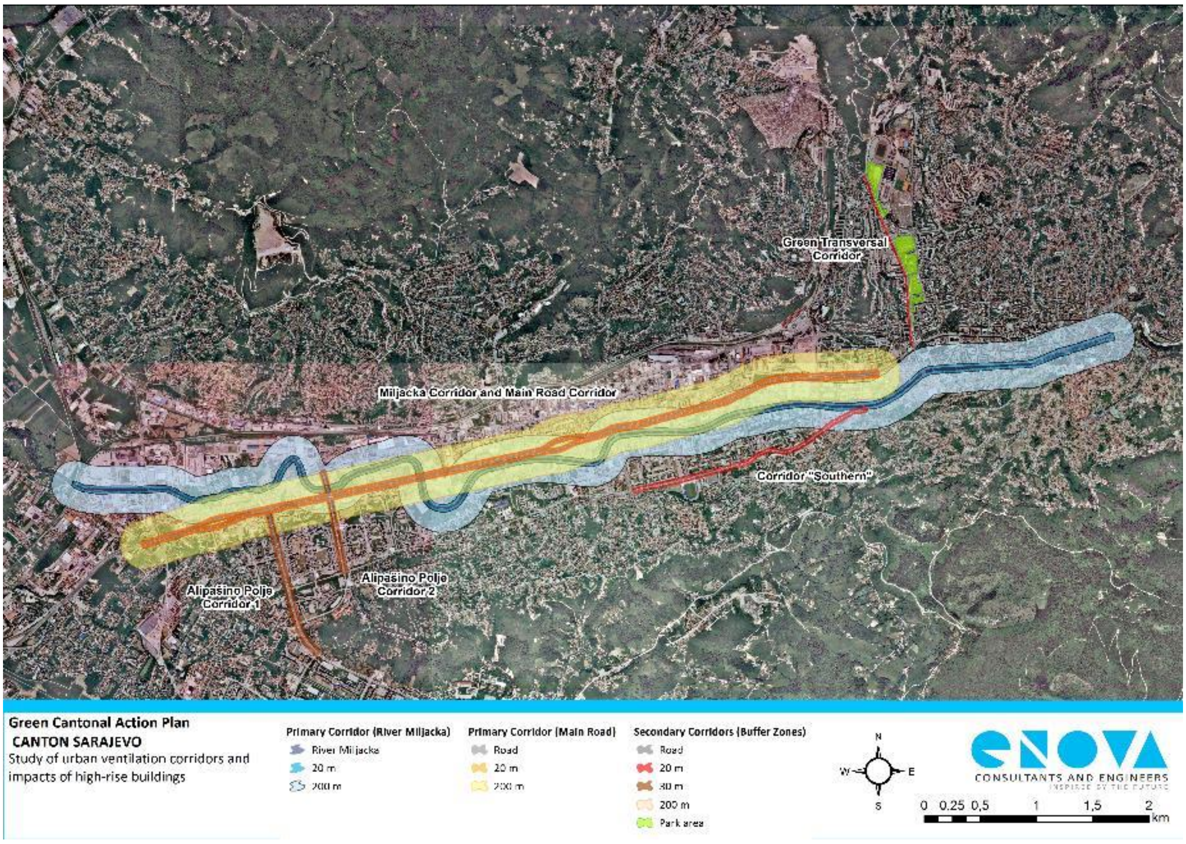
a) Primary ventilation corridors

- Miljacka Corridor: defined by the route of the Miljacka River. It stretches from the east where the Miljacka enters the city (Bentbaša) to the Miljacka River in Halilovici.
- Main Road Corridor: formed along the length of the main road connecting the eastern and western parts of the city. The corridor extends from Marijin Dvor to the east to Stupske Petlje to the west.

b) Secondary ventilation corridors

- Corridor "Southern": coincides with the "Southern longitudinal" or is defined by the following streets: Zagrebačka, Grbavička and Zvornička,
- Green Transversal Corridor: extends along Alipašina Street from Koševo and Zetra to Skenderija.
- Alipašino Polje Corridor 1: extends along Ante Babic Street in Alipašino Polje
- Alipašino Polje Corridor 2: extends along Ivo Andric Street in Alipašino Polje

Figure 10.1: Primary and secondary ventilation corridors



The primary air corridor protection measures are:

- Prevention of construction of new buildings in the 20m zone from the bank of the river Miljacka, i.e. the edge of the Main Road, on each side of the corridor.
- Building height limitation up to 20 metres (P + 6) in the 200-metre zone on each side of the primary ventilation corridors
- Maximum floor area coefficient ≤ 1
- Application of technical guidelines for spatial development and design of structures with the aim of improving the flow

The secondary air corridor protection measures are:

- Prevention of construction along the Alipašina Street-Skenderija corridor in the 20m zone on the right side of the road. Construction prohibition on park areas on the left side of the road.
- Prevention of construction of new buildings at 20m on each side of the Southern Corridor or the southern longitudinal road connecting the streets: Zagrebačka, Grbavička and Zvornička,
- Prevention of construction of new buildings on the surface of 30m on each side of the ventilation corridors Alipašino 1 and Alipašino 2, i.e. Ante Babić and Ivo Andrić streets.

In order to improve the ventilation characteristics of Sarajevo Canton and to mitigate the urban heat island effect, green corridors will be established by merging and upgrading existing green spaces (see Figure 10.2 and Figure 10.3):

- Kozija ćuprija – Bentbaša
- Northern side of Main Road corridor
    - from Veliki park – Mali Park-Hastahana;
    - greening of city yards from Dolina;
    - Fra Anđela Zvizdovića and Kralja Tvrtka Streets;
    - greening of squares along Franca Lehara Street;
    - preservation and upgrading of existing park areas between Kalemova and Kranjčevićeva Streets;
    - greening the University Campus from Halida Kajtaza street to Hamdije Čemerlića Street;
    - revitalisation and greening of the square in front of the train station and the BH Post building; and
    - preservation of existing park areas and greening of squares in the area bounded by the streets of Zmaja od Bosne and the railway station on one side, and Ložionicka and Hamdija Čemerlic streets on the other.

Figure 10.2: Green corridor along the main road

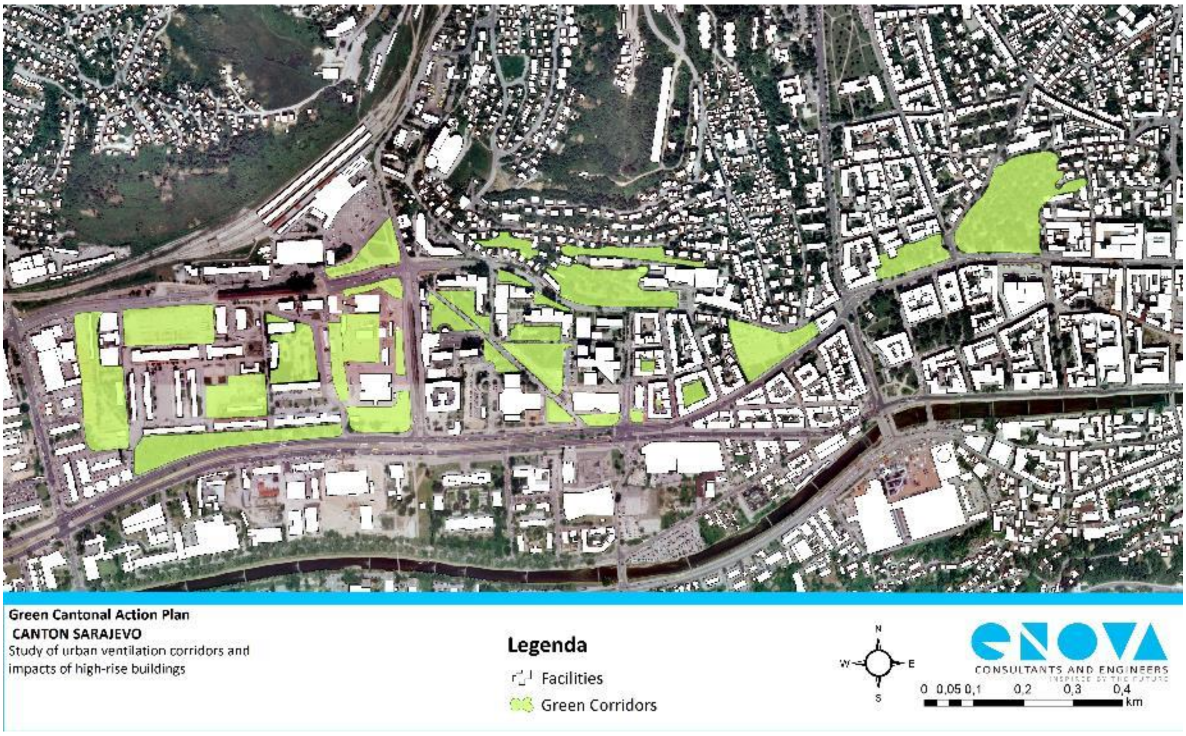


Figure 10.3: Boundaries of the green corridor Kozija Ćuprija Bentbaša

These measures shall be applied when adopting new spatial planning documents, as well as for amendments of existing ones.

When designing regulatory plans that are within the area of ventilation corridors, a strategic environmental impact assessment will be required, including airflow analysis based on numerical simulations.

An Urban Climatic Map shall be created for Canton Sarajevo, which would involve collecting and analysing relevant data on meteorology, topography and land use. Air ventilation corridors for dominant wind direction should be determined by the Urban Climatic Map and protection measures specified.

Technical guidelines shall be developed for building layout and form including based on CFD analysis that will be used as a guideline in assessing and approving new regulatory plans.

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[56] Image source: Enova overlaid on Google Maps, 2019

[57] Image source: Enova, incorporating satellite image from Google Maps, 2019

[58] Image source: Enova overlaid on Google Maps, 2019

[59] Image source: Enova overlaid on Google Maps, 2019

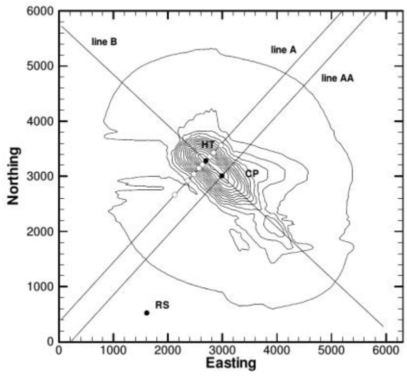
Appendix 1: Benchmark cases

We computed two standard benchmark cases in CFD in order to test accuracy and reliability of the numerical methods, turbulence model and CFD code that were used in the study. The results for both benchmark cases are in accordance with the measurements and in line with the computational results published in the past by other research groups.

Case Study 1: Askervein hill benchmark case

Askervein hill is well-documented benchmark case frequently used for validation of CFD codes for atmospheric boundary layer flow. The hill is located on the west coast of island South Uist in the Outer Hebrides of Scotland. It is nearly elliptical with the minor and major axis of 1km, and 2km respectively oriented along NW-SE direction (see Figure A.1). The height of Askervein hill is 116m from its surrounding ground (and 126m from the sea level); it is surrounded by a flat plain upwind, and with relatively larger hills downwind. The hill has a moderate slope, the surface of the hill covered with grass and some flat rocks. Aerodynamic roughness is taken to be Zo ≈ 0.03m constant based on the field measurement [64]; however, it is known that the roughness value decreases around the hilltop to 0.01m.

Figure A.1: Askervein Hill view (left) and topographic map with measurement lines (right). (adapted from [64])



In the present study domain size of 4200m x 4200m x 1000m along x, y, and z-direction is adopted by centring on the hilltop respectively. The number of grid points is 180, 180 and 36 in the x, y, and z-directions respectively. Most of the grid cells are clustered around the hill (Δx= 24m, Δy= 24m, Δz_{min}=1m). The first cell layer is 1m above the ground, and cell size expanded in the z-direction with an expansion factor of 1.2. The final mesh contains 1.2 million hexahedral cells. Incoming wind direction is 210 degrees concerning the North side. The wind direction stayed constant during the measurements, and determines the mesh orientation. The inlet is fixed on the western side of the computational domain, and the outlet is the eastern side. On the lateral side of the domain, pressure boundary is imposed, and at the top side, the symmetry boundary condition is used. The wall is modelled as a rough wall with a constant roughness height of 0.03m.

The measurements were presented by Taylor and Teunissen (1983) in a nondimensional way: the mean velocity values are given in the form of the fractional speed-up ratio (ΔS):

$$\Delta S(x, y, \Delta z) = \frac{U(x,y,\Delta z) - U_o(\Delta z)}{U_o(\Delta z)} \qquad (11.1)$$

where Δz is the height above the ground and U_0 (Δz) is the value of the undisturbed streamwise velocity at the inlet of the domain. The turbulent kinetic energy k is given in as:

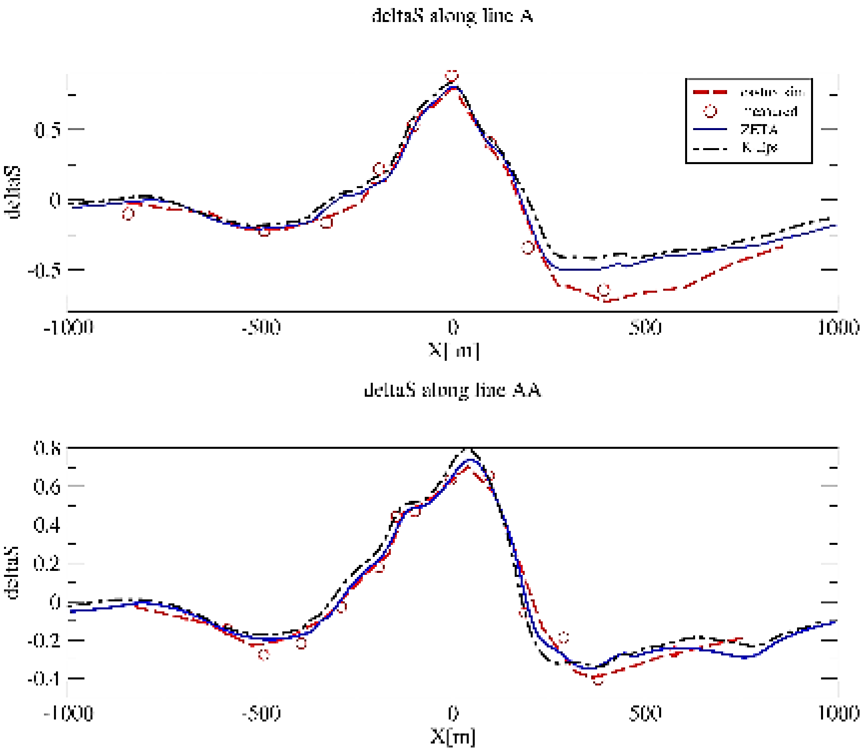
$$k^*(x, y, \Delta z) = \frac{k(x,y,\Delta z)}{U_{10}^2} \qquad (11.2)$$

where U_{10} is the mean streamwise velocity at 10 m above the ground level at RS.

The incoming wind speed is 8.9 m/s, the incoming angle is 210º, and it is assumed constant.

Figure A.2 shows a comparison of the fractional speed-up ratio for steady inflow condition along the line A and the line AA at 10 m above the ground level. The results along line AA is in good agreement with the experimental results of Taylor and Teunissen and computational results of Castro et al [61].

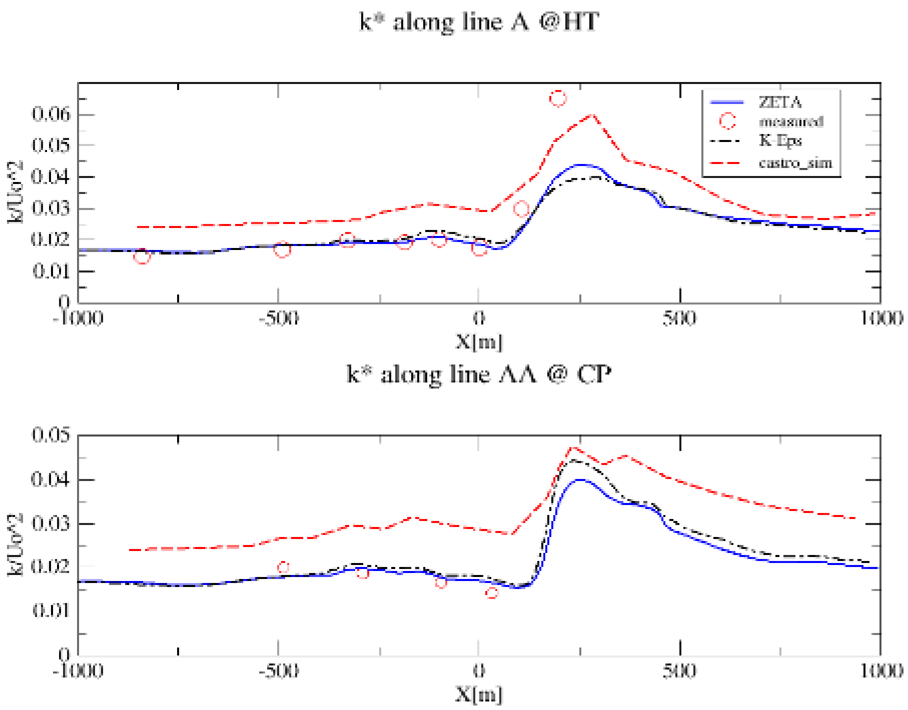
Figure A.2: Results showing ΔS along line A (upper) and line AA (lower).



Note that x =0 in the upper figure corresponds to the hilltop (HT), and in the lower centre point (CT).

The resulting values of k*(normalised turbulent kinetic energy with reference velocity at 10 m agl. at RS) along line AA and line A are shown in Figure A.3. The present results are in good agreement with experimental values on both line A and line AA.

Figure A.3: Results showing the normalised turbulent kinetic energy k* along line A (upper), and line AA (lower)



In Figure A.4 and

Figure A.5 a comparison of the vertical profiles of the fractional speed-up and normalised turbulent kinetic energy at the HT and CP with available measurements data are presented. The results are in good agreement with measurement in general, particularly ζ-f model outperformed k-ϵ model, and result published by Castro et al [61]. The k^* increased as the distance to the ground decreased particularly more visibly at HT. Experimental results indicate increasing ∆S with lower heights, but computation gives nearly constant profile below 5m agl.

Figure A.4: Vertical profiles of the fractional speed-up ratio (ΔS) (right), and normalised turbulent kinetic energy k/U_{10}^2 (left) at the HT

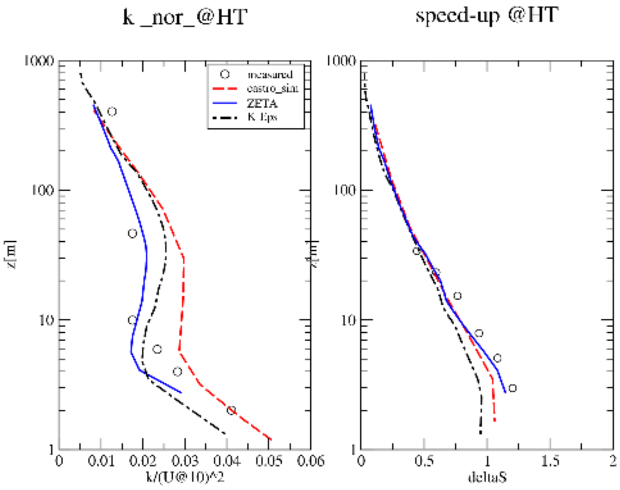
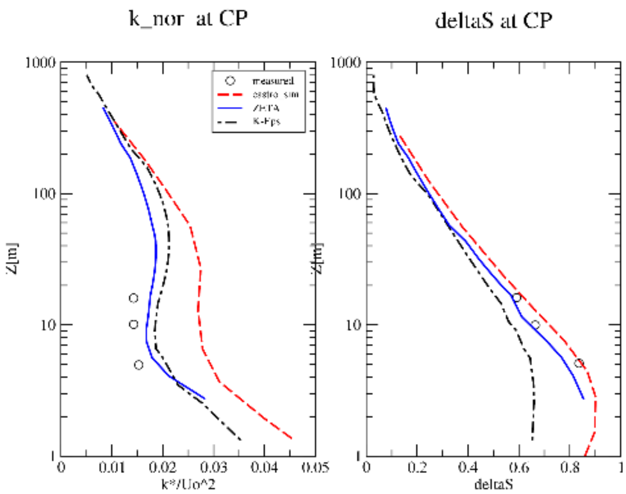


Figure A.5: Vertical profiles of the fractional speed-up ratio (ΔS) (right), and normalised turbulent kinetic energy k/U_{10}^2 (left) at the CP



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Case Study 2: Goettinger Strasse benchmark case

We performed computation of the Goettinger Strasse case, a standard benchmark case in CFD for environmental flow, particularly for predicting pollutant dispersion in the urban environment. Goettinger Strasse is a 25-metre wide, four-lane street canyon with a traffic load of approximately 30,000 vehicles per day with a share of trucks of 16% [66] located in the city of Hannover, Germany. The Lower Saxony State Agency for Ecology (NLÖ) operates a monitoring station to record pollutant concentration level caused by the traffic. The monitoring station is placed at a height of 1.5m, on the pedestrian sidewalk, close to the road edge. In addition, meteorological measurements are recorded at the anemometer which is placed at the top of a meteorological mast (10m) on the roof of the highest building (30m), from which the information about free stream velocity is extracted. The location and dimensions of the buildings are as specified in the case description provided by research network group named Optimisation of Modelling Methods for Traffic Pollution in Streets (TRAPOS) under the frame of Training and Mobility of Researchers Programme [65]

The current computation is done for north wind direction, relative to the grid, which means the main flow is parallel to the street. The main pollution source in Goettinger Strasse is the heavy traffic in this narrow street canyon with four lanes, two in each direction. To simulate this pollutant emission two line-sources of length 180m each are introduced. The emphasis is put on a certain type of pollutants, namely PM_{10} particles, which are very fine particles that have no influence on air flow and are not going through any chemical reaction. Therefore, in the current simulation the pollutants are treated as a passive scalar. The results of the simulation are presented in a non-dimensional form as follows:

$$C^* = \frac{C * U_{ref} * \mathrm{H}}{Q_e / W}$$

where, C is the instantaneous pollution concentration, $\mathrm{U_{ref}} = 10\,\frac{\mathrm{m}}{\mathrm{s}}$ is the referent velocity measured at the height of $100\ \mathrm{m}$, $\mathrm{H} = 20\ \mathrm{m}$ is the average height of the buildings in the canyon, and $\frac{\mathrm{Q_e}}{\mathrm{W}}$ is the source strength per metre, where the distance is taken to be the width of the pollution line-sources $\mathrm{W} = 11.8\ \mathrm{m}$.

Figure A.6: Computational grid of the whole domain for Goettinger Strasse, top view

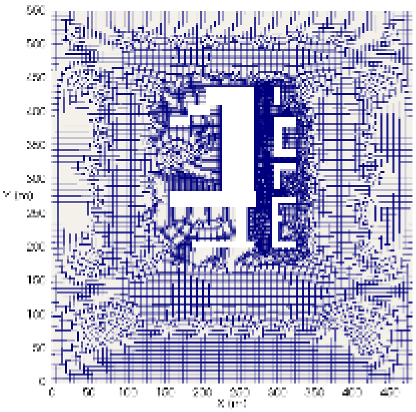
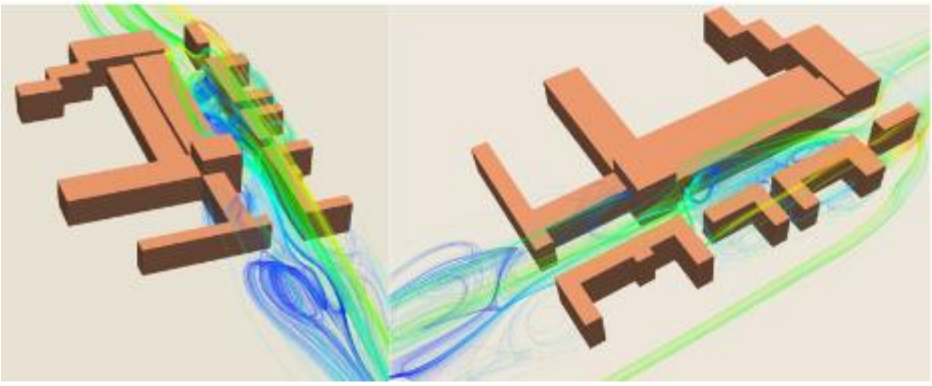


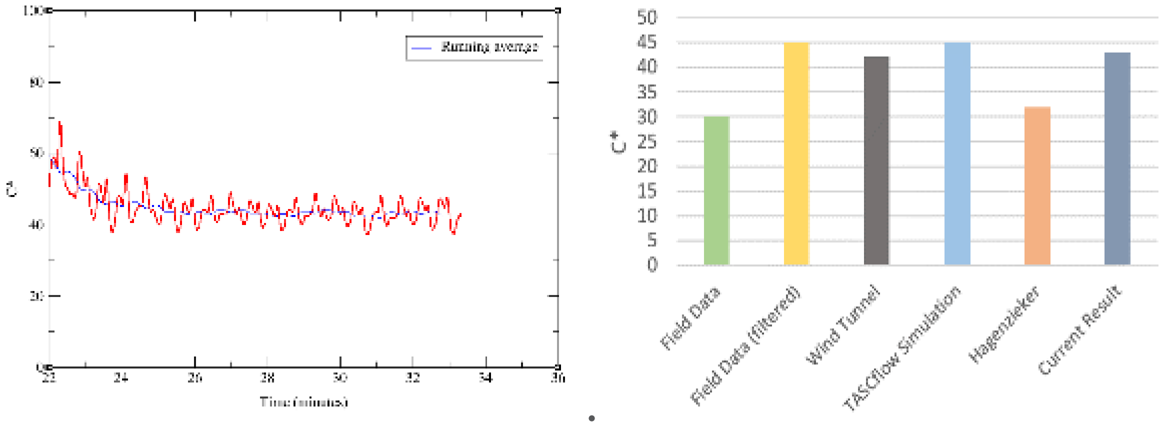
Figure A.7: Google Maps screenshot of Goettinger Strasse from 2019 with contours of the buildings and simplified geometry used in this work

Figure A.8: Streamlines along the centre of Goettinger Strasse showing complex flow pattern.



The current simulation result for non-dimensional pollution concentration level at the measuring station after it has reached statistical steady state compared to the measuring and computational data of other authors are shown in Figure A.9. The inability of C^* to converge to a steady value confirms the complex pattern of the flow and its unsteadiness. The simulation was run for 50,000 time-steps, with the size of a time step $0.04\,s$, which results in approximately 33 minutes in real time. The simulation was stopped when it was agreed that the concentration level exhibits repeatable oscillations.

Figure A.9: Current simulation results for the non-dimensional air pollution at the measuring



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