AIR QUALITY MANAGEMENT

IN GLASGOW'S AVENUES

Strategies for Public Realm Design and 'Avenues' Programme

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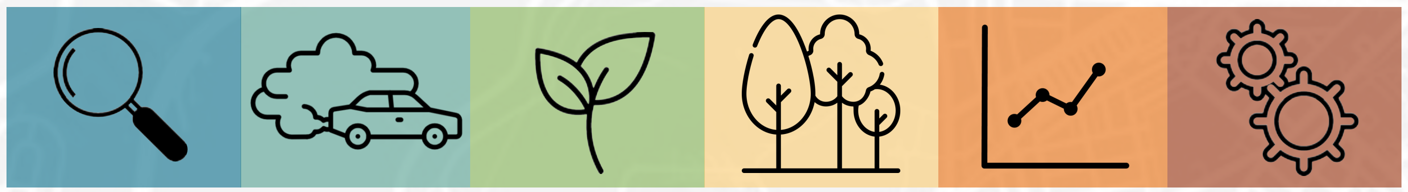


GLOSSARY

PM	-	Particulate Matter
PM_{10}	-	Particulate Matter With a Diameter of 10 Micrometers
$PM_{2.5}$	-	Particulate Matter With a Diameter of 2.5 Micrometers
NO_2	-	Nitrogen Dioxide
LEZ	-	Low Emission Zone
NBS	-	Nature Based Solution
AQMA	-	Air Quality Management Area
PRD+MG	-	Public Realm Design + Maintenance Guide
AR	-	Aspect Ratio

EXECUTIVE SUMMARY

Urban air pollution is one of the biggest environmental threats and health concerns in the world. Protecting the health and wellbeing of the urban population has become a significant challenge for planners. In the past decade, many countries have developed sanctions and policies to control air pollution and human exposure in cities.

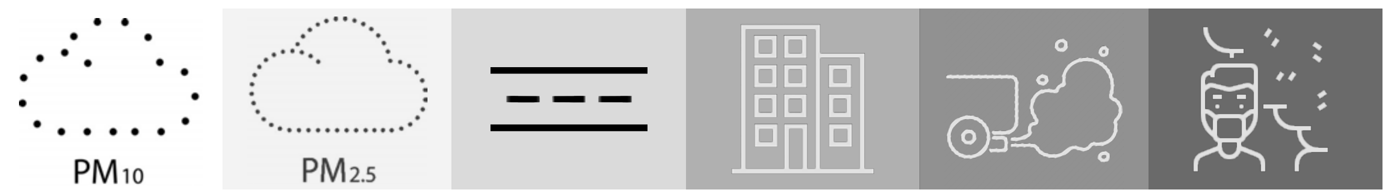
In recent years, street vegetation has been identified as an alternative nature-based solution to improve urban air quality. In urban planning, positioning the right vegetation in the right place is vital for air quality enhancement. This study proposes street design guidelines for pollutant dispersion in streets of Glasgow city-centre.

Based on a calibrated model using existing air quality measurements in one of Glasgow's most polluted streets, different street tree scenarios and cases were developed, corresponding to *Glasgow's 2021 Public Realm Design + Maintenance Guide* and *Avenues Programme Design Scheme*.

The impact of different in-canyon placement strategies of vegetations, and street tree parameters such as tree shape, porosity, size, species, etc. were evaluated along with meteorological parameters such as wind directions, which plays a crucial role in urban street planning and air quality enhancement.

The findings indicate streets trees as an effective strategy to improve the air quality in Glasgow City Centre, especially when implemented on the leeward side of the street. It also showed that trees are more effective when planted based on the respect ratio of the street which otherwise can negatively impacts the air quality in the city.

Our findings on the optimum street trees planting strategies are complimentary to the *Glasgow Avenues Programme* and could provide environmental co-benefits for a better local future.



SOMETHING IN THE AIR . . .

The air we breath is a vital and a constant need for all life on Earth. However, in cities, it is getting harder to breathe, because something in the air is threatening human health and the natural world.

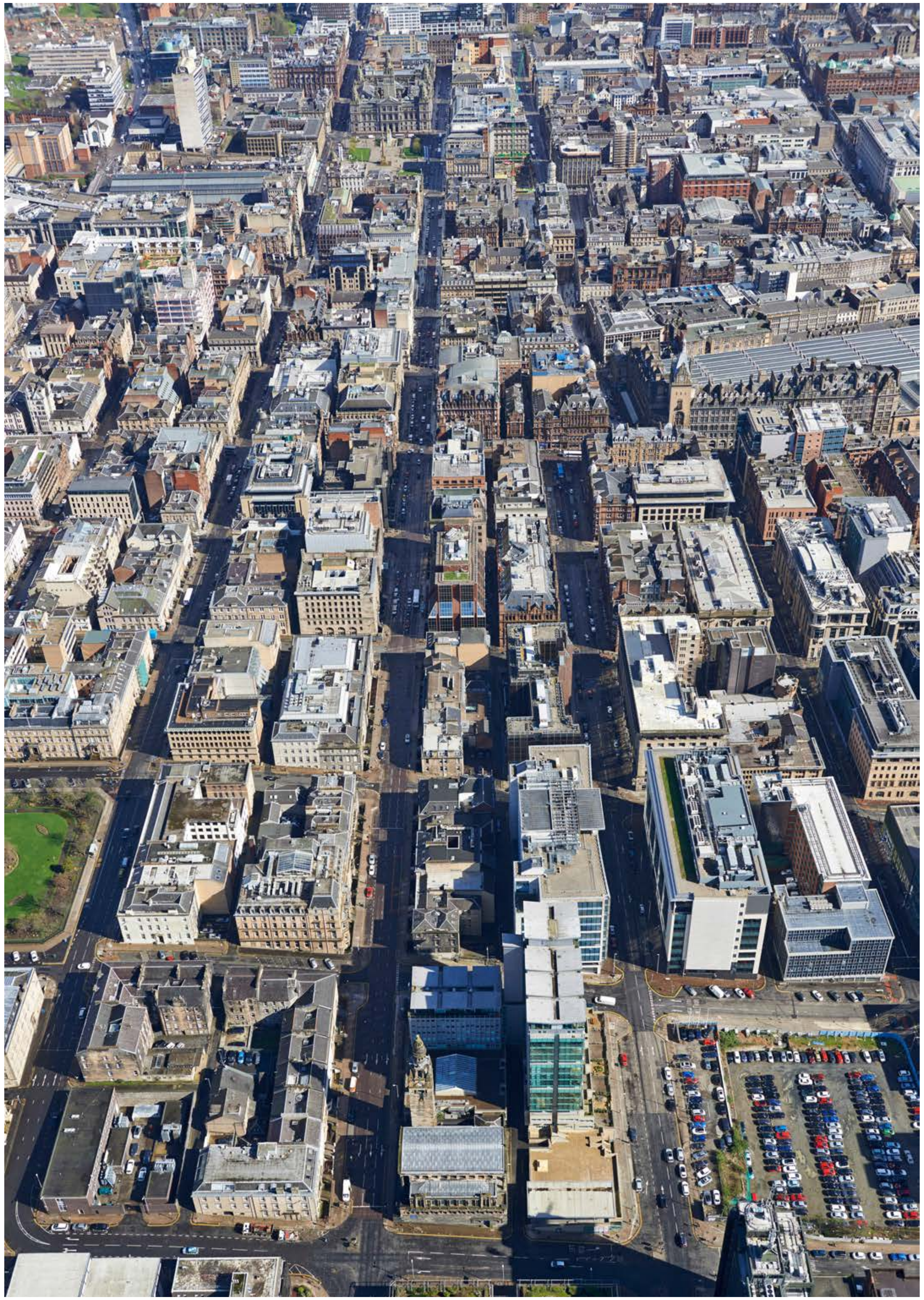
Air pollution is the biggest environmental health hazards in the UK. With **vehicular traffic** being a major source for harmful pollutants due to the combustion of fossil fuel, air pollution in urban environments has become a serious concern.

In Scotland, the increasing car dependency in Glasgow has led to some of the most polluted streets in the country, which repeatedly breached the Scottish, WHO and EU safe limits in the past decade (Figure 01). Hope Street is one such street in Glasgow with high pollution levels, particularly, **Particulate Matter** (PM); the most dangerous pollutant found in Scottish cities due to its adverse health effects.

Over the past decade, air quality in Hope Street has significantly improved. The average $PM_{2.5}$ of 8.3 µg/m³ recorded in 2010 reduced to 5.9 µg/m³ by 2020. However, in 2021, when Covid restrictions were eased, $PM_{2.5}$ increased to 6.9 µg/m³, causing around 400 premature deaths in the city (IQAir, 2022). This calls for more effective measure to improve Glasgow's air quality.

In addition, the existing morphology of the city centre with high-rises and inadequate safe spaces for pedestrians, cyclists and vegetation, prevents the dispersion of polluted air from Glasgow streets, causing clear damages to the quality of life of it's inhabitants.

As most air pollutants are 'short-lived climate forcers', air pollution is closely linked to climate change.



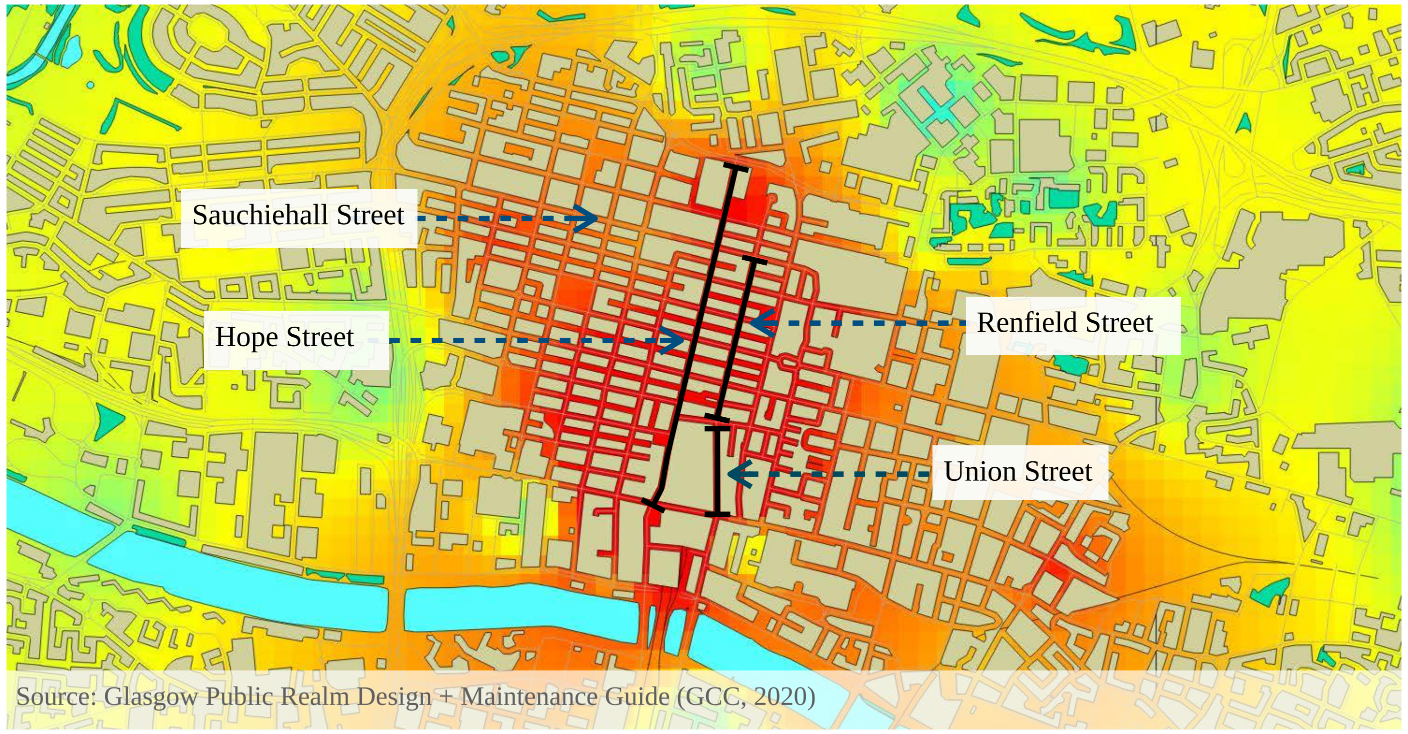


Figure 01: Most to least polluted streets in the City Centre (By black, red, orange, yellow, green, and blue) - 2013.

GLASGOW AIR QUALITY MANAGEMENT

With a target to reduce both atmospheric NO_2 and PM, Glasgow City Centre was declared as an Air Quality Management Area (AQMA) in 2004. Air Quality Action Plans under the AQMA introduced a range of emission control measures to shift Glasgow from a 'car-oriented' to a **'sustainable mobility'** city. Furthermore, the city targets to achieve carbon neutrality while reducing vehicle kilometres travelled in the city centre by 30%, by 2030 compared to 2019 levels.

Key Actions

- Initiation of a Low Emissions Zone (LEZ) within an emerging national framework.
- Introduction of Avenues Project on several key streets in the city centre under the City Centre Strategy.
- Glasgow Transport Strategy to improve transportation hierarchy for street users; prioritising walking > cycling > public transport > private car.

URBAN TREES AND THE AIR WE BREATH

In urban planning, trees are promoted as a viable **Nature-Based Solution** (NBS) to improve air quality and human health. Over the years, many models have been developed for various scientific purposes to predict pollutant removal capacity of trees. These models identify trees as a porous medium which alters the air quality by influencing localised aerodynamics and natural dispersion patterns while promoting filtration and deposition of pollutants as shown in Figure 02.

Key Factors

- In an urban context, pedestrians are most vulnerable to pollutants in urban street canyons due to high vehicle emissions and reduced pollution dispersion.
- Urban canyons significantly influence air quality at street level based on the presence of obstacles (vegetation, billboards, etc.), wind flow, traffic accumulation and the Aspect Ratio (AR).

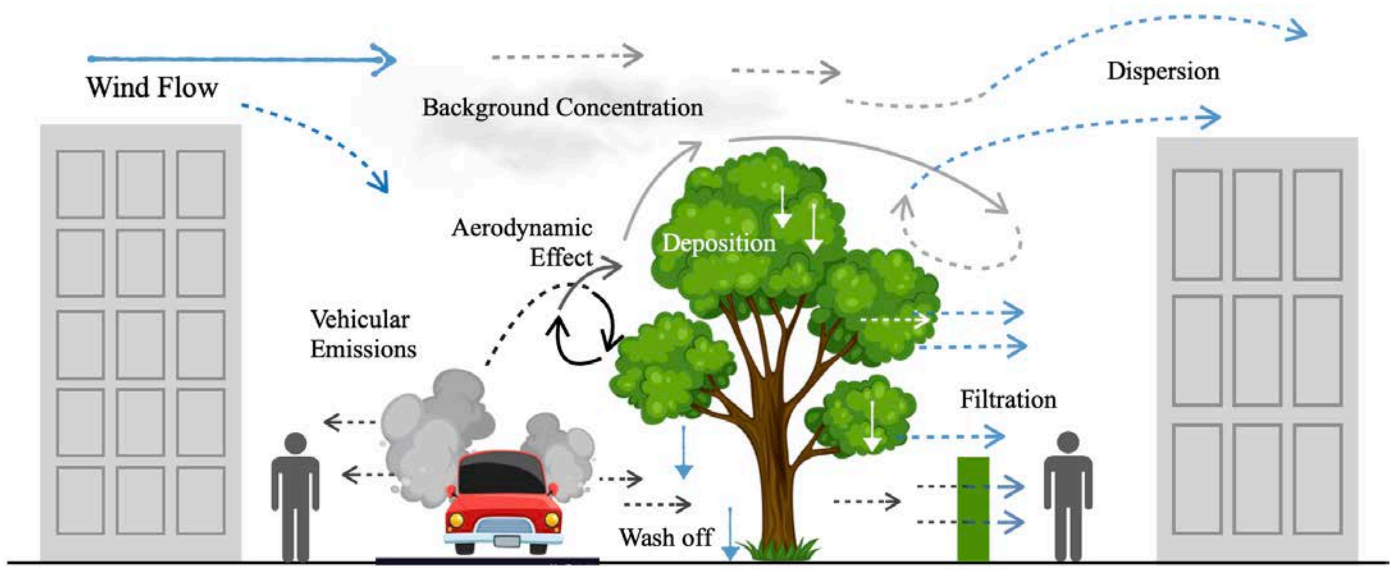


Figure 02: Impact of trees as a porous media in reducing air pollutants.

Moreover, urban policies and NBS are separate strategies utilised to improve air quality, although they should be regarded together to obtain a **combined effect**. Such understanding can be crucial for future city planning, as it can drastically reduce atmospheric particles, benefit public health, social well-being, and sustainable development of cities in the process of tackling challenges in air pollution.

With this in mind, the project aimed at **critically analysing street tree planting strategies as an approach to reduce PM in Glasgow City Centre**, in support of urban planning and LEZ.

THE APPROACH

In the context of the 'Avenues Programme,' the following study protocols were employed:

Evaluation of air quality records from the Kerbside Measuring Station, calculate aspect ratio and hourly vehicular patterns in Hope Street

Formulation of tree placement strategies considering,

- **In-canyon placement**
- **Tree spacing requirements.**

Formulation of Case Studies considering existing trees in Sauchiehall Street

- **Tree canopy configurations**
- **Vegetation species**
- **Wind directions**

Run ENVI-met 5.0.3 to model Hope Street and Sauchiehall Street to systematically study the impact of tree on local air quality;

- **Conducting model validation**
- **Development of Base Model, Six Scenarios and Seven Cases**

Propose recommendations for green interventions in support of urban planning and city development in Glasgow

Assessment of individual and combined effects of street trees and street geometry on air quality

The study area for the assessment was narrowed down to north-south oriented 'Hope Street' as the *Test Site.* After calibrating a model using existing air quality and street canyon data on Hope Street, the assessment was conducted under two studies.

Sensitivity Study evaluated the impact of six distinct in-canyon tree placement strategies, as shown in Figure 03, i.e. Scenarios 01, 02 and 03 having leeward trees with 1.2m, 6m and 10m canopy gaps, respectively, while Scenarios 04, 05, and 06 having windward trees with respective canopy gaps. It utilised a recorded wind speed of 3.5 m/s in perpendicular direction (270°), i.e. westerly winds.

Case Studies evaluated the impact of tree size, shape, porosity, specie, type, and oblique and parallel winds as shown in Figure 04.

For this series, placement scenario which reduced a substantial percentage of pollutants under the sensitivity study was selected for assessment.

The simulation results of all six scenarios and seven case studies (Figure 03 and 04) were evaluated from different perspectives to fully understand the impact of street tree on PM, with regard to the *Base Model* (BM) which directly replicated the existing Hope Street. Each scenario and case study had a mix of *Acer platanoides, Acer campestre, Carpinus betulus, and Ginko biloba* in fastigiate shape; as available in Sauchiehall Street; the pilot project of Avenues Programme.

Finally, the reliability of the findings derived from Hope Street's analysis was verified utilising a model calibrated to 'existing data' on the east-west oriented Sauchiehall Street as the *Control Site.*

Six Scenarios					
In-Canyon Leeward Placement			In-canyon Windward Placement		
Scenario 01 Canopy Gap: *1.2m* No. of Trees: *56* Stand Density: *6.2%*	**Scenario 02** Canopy Gap: *6m* No. of Trees: *34* Stand Density: *3.8%*	**Scenario 03** Canopy Gap: *10m - 12m* No. of Trees: *28* Stand Density: *3.1%*	**Scenario 04** Canopy Gap: *1.2m* No. of Trees: *62* Stand Density: *6.9%*	**Scenario 05** Canopy Gap: *6m* No. of Trees: *33* Stand Density: *3.7%*	**Scenario 06** Canopy Gap: *10m - 12m* No. of Trees: *27* Stand Density: *3.0%*

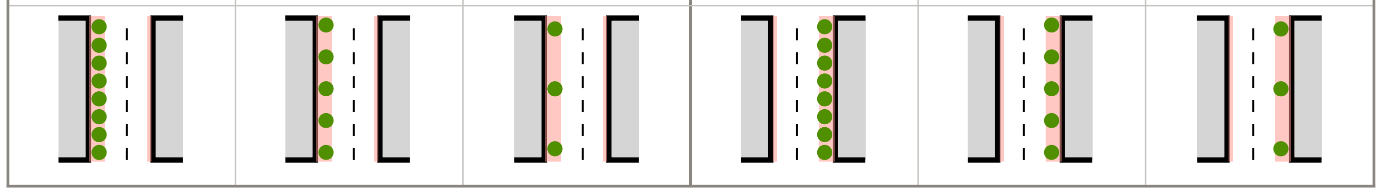


Figure 03: Six street tree placement scenarios

Seven Case Studies					
In-Canyon Leeward Placement			In-canyon Windward Placement		
Case 01 Increased height and width. To analyse the impact of tree size variations on air quality	**Case 02** Crown Geometry: Spherical To understand its influence on particle behavioural	**Case 03** Increased Canopy Porosity To study the effect on particle dispersion, deposition and aerodynamic effects	**Case 04** A set of different tree species To investigate the possibilities of using better trees	**Case 05** Additional row of hedges To understand the impact of increasing green cover through vegetation types	**Case 06 and 07** Case 06: Impact of oblique winds (225°) Case 07: Impact of parallel winds (180°)

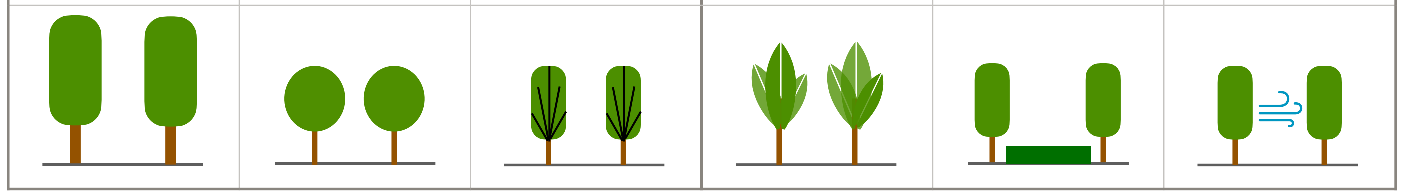


Figure 04: Seven cases for air quality analysis

THE TREES WE NEED . . .

Can we systematically use street trees to improve the urban air quality, subsequently, supporting urban planning and policies?

If yes, then How?

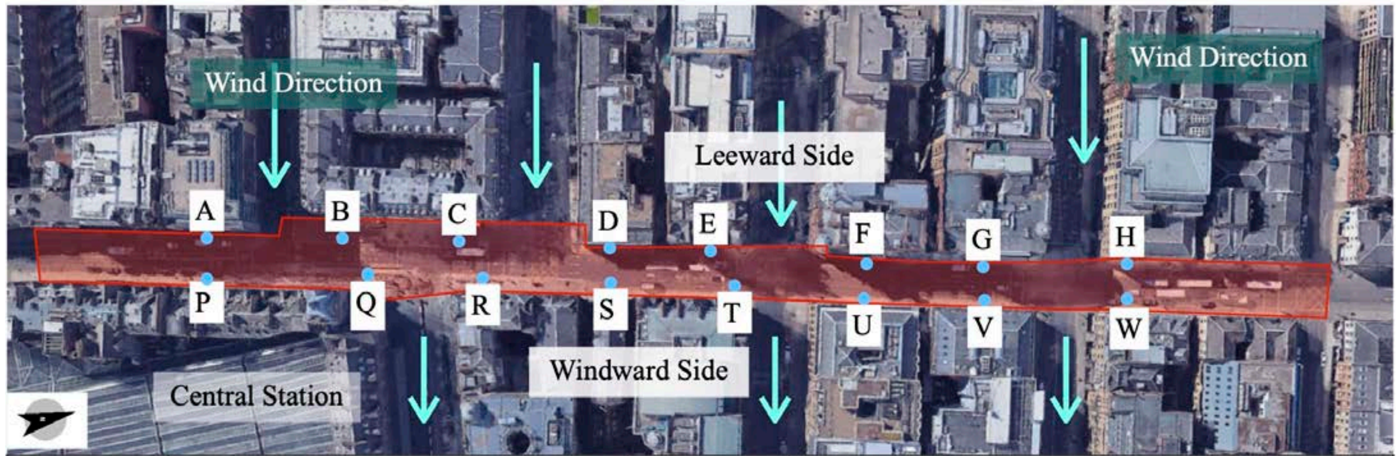
SENSITIVITY ANALYSIS

In all six scenarios specified above, the receptors from which PM data was obtained are presented in Figure 05 along with their respective AR. The analysis accounted the impact of PM_{10} and $PM_{2.5}$ separately. However, in all accounts, both particles showed similar behaviour patterns on both leeward and windward sides of the street.

a. Particle Matter Analysis

Under this analysis, relative difference of the day's average PM concentrations were evaluated for the leeward and windward sides separately, as shown in Figure 06.

Scenario 03 achieved the largest PM reduction due to aerodynamic and deposition effect as a result of increased gap between canopies.



Receptors	A/P	B/Q	C/R	D/S	E/T	F/U	G/V	H/W
Aspect Ratio	1.72	1.01	1.01	1.02	1.68	1.51	1.71	0.92

Figure 05: Receptor points and their respective AR

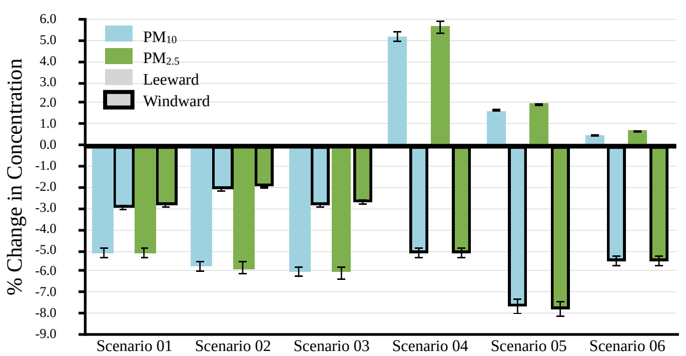


Figure 06: Day's average PM concentration for six scenarios

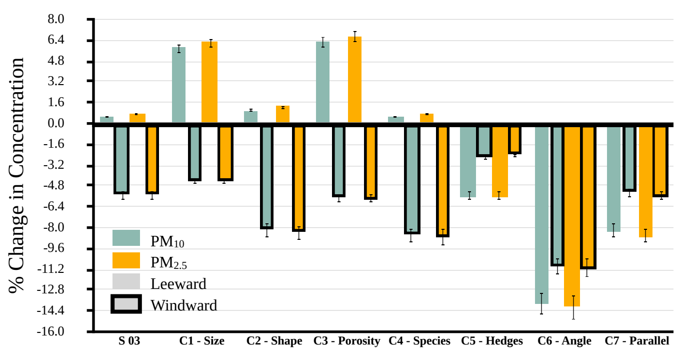


Figure 07: Day's average PM concentration for seven cases

b. Tree Placement Analysis

This section analysed the impact of different canopy gap between trees on the behaviour of PM.

On leeward scenarios, larger gaps removed more particles in the street due to increased air exchange. However, in windward scenarios, it resulted in particle accumulation due to low winds

c. Temporal Distribution Analysis

Temporal Distribution analysis obtained hourly average particle concentrations separately from leeward and windward side for the evaluation. It detailed out the impact over a span of 24h.

Leeward tree scenarios removed more particles throughout the day, especially during peak hours, compared to windward tree scenarios.

d. Spatial Distribution Analysis

Spatial distribution analysis evaluated the day's average PM concentrations obtained from each individual receptor. With eight separate receptors from the leeward and windward side each, it searched for the impact of in-canyon placement of trees across Hope Street with reference to its AR.

Planting trees in shallow canyons, at building setbacks and centre of deep canyons deteriorate the air quality, although trees in smaller street blocks improve the air quality through dispersion and deposition effects.

CASE STUDY ANALYSIS

In this series, all cases followed the tree planting strategy of Scenario 03. It considered the relative difference of the day's average PM concentrations with reference to the BM to evaluate the impact of various vegetation properties and wind directions on PM, as shown in Figure 07.

a. Influence of Canopy Configurations

Under this section, Case 01, Case 02, and Case 03 were evaluated reflecting the most common canopy configurations regarded in urban planning.

With reference to Scenario 03, increasing tree size and canopy porosity deteriorated the air quality by obstructing the wind flow and fostering particle accumulation in urban canyons. Altering canopy shapes however didn't have a deep impact on PM.

b. Influence of Alternative Species and Hedges

This section evaluated Case 04 with different tree species (high pollutant tolerance; low pollen and VOC emissions) suitable for UK streets, and Case 05 with additional rows of 0.9 m height hedges.

Both cases had similar impact as Scenario 03, but with finer deposition and aerodynamic variations.

c. Influence of Alternative Wind Directions

Considering the dominant wind directions in Glasgow, this section analysed Case 06 with oblique winds (225º) and and Case 07 with parallel winds (180º), referring to Scenario 03.

Tree placement strategy in Scenario 03 had positive outcomes under all wind directions. However, the most PM reductions were observed under oblique winds as shown in Figure 08.

d. Spatial Distribution Analysis

The day's average particle distribution of all the cases were analysed in this section with reference to the BM and Scenario 03.

All cases negatively influenced the air quality in deep canyons, at the centre of street block and areas with building setbacks. However, enhanced the air quality near street intersections, due to corner eddies and vortexes induced by wind flow.

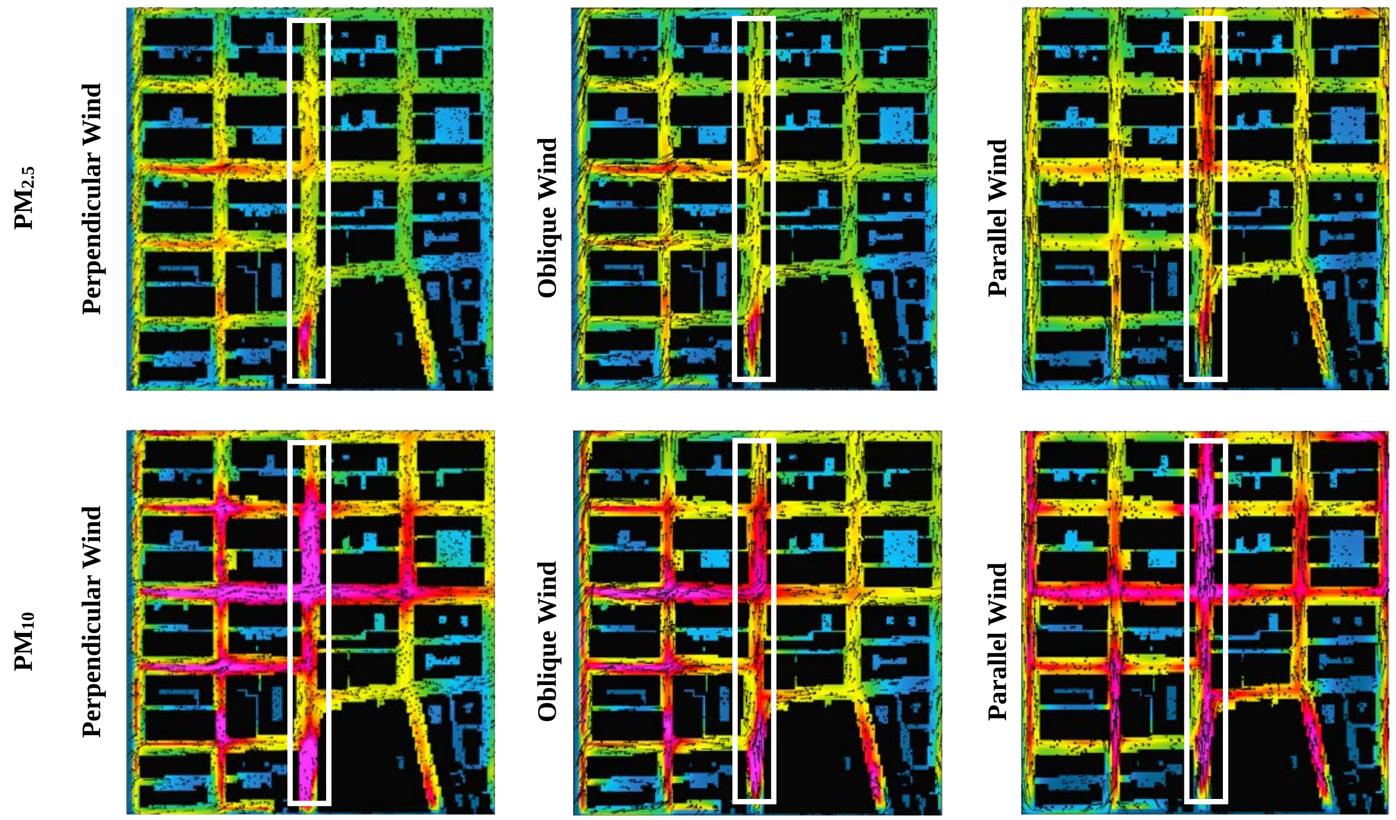


Figure 08: Behaviour of PM_{10} and $PM_{2.5}$ under different wind directions at 12:00 noon

IMPACT ON OTHER POLLUTANTS

This section investigates the impact of Scenario 03 on NO, NO_2, NOx as NO_2 and ground level O_3 in comparison to the BM as seen in Figure 09. Trees reduce gaseous pollutants by stomatal absorption.

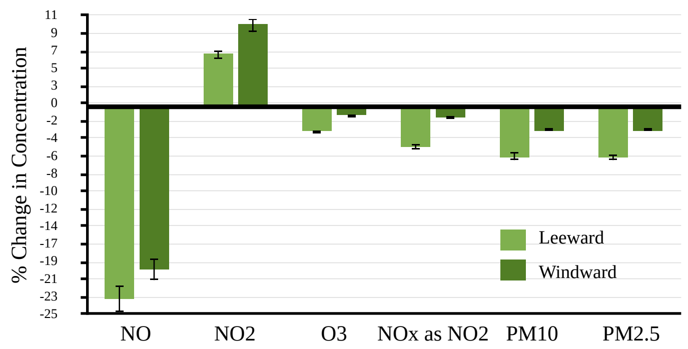


Figure 09: Percentage change of other pollutants in S-03

Scenario 03 reduced a significant amount of NO on both sides of the street, unlike NOx as NO_2 and O_3 which reduced smaller quantities. However, it deteriorated the NO_2 concentration, likely due to prevailing aerodynamic effects which outweigh the filtering capacity of NO_2 by trees.

VALIDATION OF FINDINGS

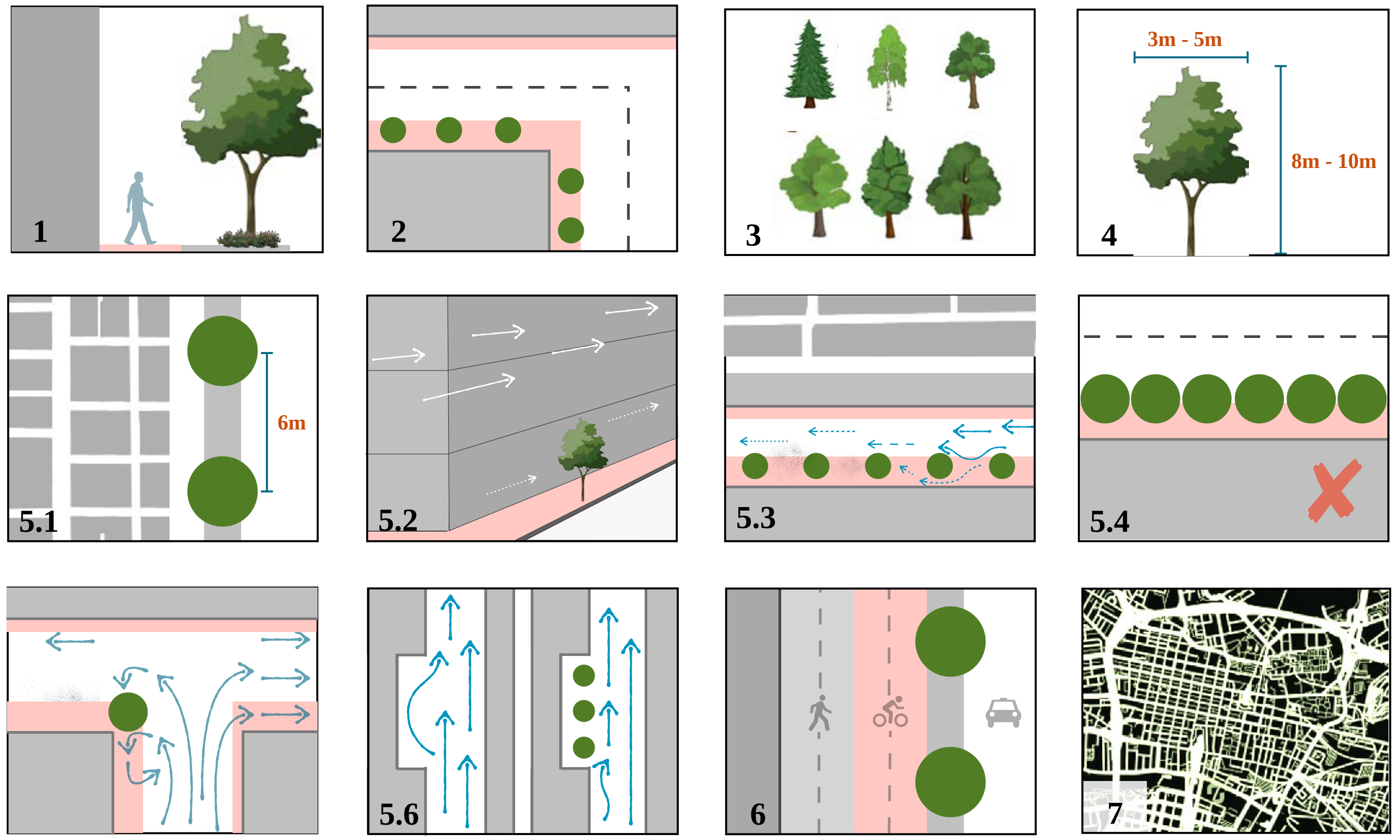
A separate simulation analysis was conducted for the validation of above findings from the Hope Street analysis. This was initiated through a separate simulation analysis by employing two models generated for Sauchiehall Street.

1. *Control Model* - Reflected existing conditions of Sauchiehall Street with windward trees.
2. *Sample Model* - Removed and replaced existing windward trees with leeward trees placed at 10m intervals to assess the impact of tree placement strategy of scenario 03.

The PM concentration on the respective side of street with trees, improved the air quality in both models. However, overall behaviour of PM in the Sample Model was comparatively lower, implying that the presence of trees has a significant impact on urban street air quality enhancement under the right tree planting configurations.

IMPLICATIONS FOR URBAN PLANNING

This section discusses the street tree planting implications with reference to the respective diagram below.



1. implement trees in the city centre

Trees perform better when they stand alone rather than in combination with hedges. However, low-level vegetation such as grass or raingarden scrubs can be used to enhance the air quality.

Hedges require higher maintenance and growing space; sometimes disrupt ventilation and obstruct the view causing danger to people with a visual impairment. On the other hand, trees provide benefits such as shading, urban cooling, flood prevention, thermal comfort, etc.

2. Street trees and wind regime

In Glasgow, the dominant wind directions range from south to west. Hence, for North-South oriented streets it is ideal to position trees towards the western side, while in East-West streets it is ideal position trees towards the southern side.

Under perpendicular and oblique winds, placing trees towards the side of the wind direction creates better wind turbulences and influence air exchange. As a result, it removes an acceptable amount of air particles from the street.

3. Ideal tree species to improve the air quality

Existing trees in Sauchiehall Street, (Acer platanoides 'Deborah', Acer campestre 'William Caldwell', Carpinus betulus 'Fastigiata' and Ginko biloba) has an ideal configuration at semi-maturity for air quality enhancement. These species have a high to moderate tolerance to pollutants and low to moderate emission of VOCs.

In addition, species such as Tilia, Sorbus and Pinus can be utilised due to their high air quality enhancing properties, such glossy, wooly and hairy leaf textures with a better tolerance to pollutants and lower VOC and pollen emissions.

4. Utilising the right canopy structure

Tree canopies with low porosity in either spherical or cylindrical shape is suitable to encourage infiltrations of particles. However, tree height needs to be maintained at 8m - 10m with a canopy diameter between 3m - 5m due the structure of street canyon geometries in the city centre.

This composition benefits particle reduction in Glasgow City Center through dispersion, deposition and aerodynamics effects.

5. Tree spacing and street geometry

The spacing between street trees should be decided based on the aspect ratio of the street, as it can otherwise deteriorate the air quality.

For instance;

5.1. In streets with compact uniform canyon or small block lengths, it is possible to maintain a 6m gaps between trees to reduce particles.

5.2. In deeper street canyons, wind velocities are relatively lower and particle concentrations are usually higher towards the centre of the street. Hence, planting trees in isolation with reasonable distances encourage particle dispersion and deposition.

5.3. In areas with long block lengths, despite the canyon geometry, it is ideal to place trees with larger canopy gap as the wind speeds relatively slows down towards the centre.

5.4. At all instances, it is ideal to avoid rows of densely placed trees as it can obstruct the wind flow and trap particles within the street.

5.5. Tree placement near intersections obstruct corner eddies and discourage wind flow into street canyons increasing PM concentrations.

5.6. Introducing trees in street canyon areas with building setbacks deteriorate the air quality as natural particle reduction capacities through dispersion is at its maximum without trees in these areas.

6. Sidewalks and cycle tracks

Designing walking and cycling tracks between the building line and the tree line on the specific side of the street can provide safer commuting experiences for both pedestrians and cyclists.

As the air quality improves by the row of trees (ideally placed considering the wind regime), it creates a healthier atmosphere. This can reduce pedestrian exposure to polluted air, as well as provide protections from potential accidents.

7. Urban morphological changes

Above guidelines provide solutions for the current air quality demands in Glasgow. It accounts the existing properties of the urban morphology (building layouts and street canyon geometries) in the City Center.

By accounting future changes to Glasgow's urban fabric, it is possible to make these strategies time-dependent (short, medium and long-term use).

Given the current focus on street trees in the city centre, the present research findings could also be considered for LEZs to "co-benefit" Glasgow's air quality. However, it needs to be carefully assessed alongside other benefits to eliminate challenges in the process and be extended to similar Scottish urban centres as they contain similar urban structures and meteorological conditions.

Since Glasgow is also one of the most vulnerable cities to climate change and as climate change and air pollution are interlinked in a broader scale, NBS addressing air pollution can ultimately provide direct and indirect benefits for climate vulnerabilities and aid Glasgow to become a climate resilient sustainable compact city by 2036.

CHALLENGES

Planting trees can be challenging in existing urban street canyons, based on the availability of space, site conditions, maintenance requirements, etc. although it is not entirely insuperable.

As street trees can be planted in numerous ways, finding the right orientation within a street canyon can be a challenging task, especially when a single street canyon within a city contains a series of different aspect rations.

In densely built street geometries, such as in Glasgow, allocation of space for trees can compromise room for sidewalks or vehicle lanes. Hence, it is vital to thoroughly reflect on the city's development plans, policies, budget and the vision before utilising street trees to avoid social and economic consequences, such as traffic and disturbances for daily movement. If not, fragmented authorise and scattered development plans can further cause complications and costly updates across the city centre.

In addition, in tight urban spaces, tree roots can also cause costly damages to infrastructure and building foundations if trees are not properly installed or maintained. Inadequate maintenance can also affect the health of the plant relating to viruses, fungi, bacteria, insects, etc.

OPPORTUNITIES

Opportunities of street trees can be categorised as environmental, economic or societal, leading to a sustainable urban growth. Apart from its impact on air quality, street vegetation plays an integral role in influencing the surrounding atmospheric conditions, and as a result reduce the energy consumption, storm water runoff, noise pollution, etc., while improving local biodiversity, thermal comfort, shading and urban cooling.

In Glasgow, street trees can provide an ideal base for high quality walking and cycling experiences in the City Centre. By implementing the finding of this research, it will not only protect human health but also address climate vulnerabilities in the city.

While supporting the core values of the Avenues Programme in Glasgow, i.e. to beautify the City Center and interlink communities with public spaces, systematically planting trees can also provide sustenance for the LEZ framework and support redesigning of road transportation within the city centre.

As trees can result in reducing crime rate and increasing property values, systematic tree placing can support the rebranding and regeneration of city's imageability and transform the existing urban fabric as a climate conscious, sustainable tourist destination.

Funding for this publication was provided by the GCU Knowledge Exchange Stimulation Fund. Research underpinning the publication was funded by the Erasmus Mundus Joint Master Degree programme – Master of Urban Climate and Sustainability (MUrCS, www.murcs.eu), European Education and Culture Executive Agency (EACEA), Grant No: 2017-1926

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ISBN 978-1-7398476-2-3

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Cover Background Image: stock.adobe.com/lk/

Published online on March 2023, Glasgow, Scotland, UK.

9 781739 847623

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