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INTEGRATED ASSESSMENT OF REGULATING ECOSYSTEM  
SERVICES IN URBAN AREAS  
(ИНТЕГРИРАНА ОЦЕНКА НА РЕГУЛИРАЩИ ЕКОСИСТЕМНИ  
УСЛУГИ В УРБАНИЗИРАНИ ТЕРИТОРИИ)

Thesis summary  
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The thesis consists of a title page, content, list of abbreviations, list of figures, list of tables, introduction, five chapters (publications), synthesis, reference list, appendices and statement of originality.

The thesis is 201 pages, including 61 figures, 13 tables and 285 references. The public defence of the thesis will take place at a meeting of the scientific committee on ..... at ..... h at the National Institute of Geophysics, Geodesy, and Geography – Bulgarian Academy of Sciences, room 101, with the following committee members:

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The defence materials are available to those interested in room 105 at the NIGGG-BAS and at the following website: <https://niggg.bas.bg/>

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## Chapter 1: Introduction

### 1.1. Overall motivation

Urbanisation is identified as one of the key major demographic trends that determine our world (United Nations 2024), however, it is also one of the main drivers for the diminishing of the protected habitat types and species under protection (Regulation 2024/1991). With the world population expected to increase by 2050, the percentage of people living in urban environments will be above 70% (Wahba Tadros et al. 2021). Urban areas are defined as built-human settlements characterised by high population density (Vallecillo et al. 2022). This term could be interpreted in a narrow and broad perspective. The wide perspective identified urban areas as the high densely built-up areas and their surroundings. The particular perspective is narrowed up to the only built-up area, where people live (Vallecillo et al. 2022). Urban ecosystems could be outlined as complex ecosystems, whose heterogeneity leads to highly diverse fine-scale land cover and land use (Maes et al. 2013; Keith et al. 2020; Vallecillo et al. 2022).

Urban green infrastructure (UGI) and nature-based solutions (NbS) are key concepts for addressing Sustainable Development Goals (SDGs) (United Nations 2015; Marando et al. 2019; Wickenberg et al. 2021), especially Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable, Goal 13: Take urgent action to combat climate change and its impacts, and Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. SDG11 and SDG13 overlap regarding implementing urban heat island (UHI) effect and air pollution regulation approaches within cities (Tate et al. 2024). SDG15 has been addressed mostly in studies of the application of UGI for reducing urban flood risk and improving stormwater management (Tate et al. 2024).

The concept of ecosystem services (ES) (Costanza et al. 1997; Daily 1997; MEA 2005) is based on the interdisciplinary approach for their assessment, which integrates multiple scientific spheres. The concept is directed to the acknowledgement of the benefits, that people derive from ecosystems (MEA 2005). The term ecosystem services includes ecosystem goods and services and combines all goods (material) and services (non-material processes) benefits that people derive from well-functioning ecosystems. The ES could be classified into different groups, based on their functional characteristics (De Groot et al. 2002). In this study, we use CICES 5.1, developed for environmental accounting purposes by the European Environmental Agency (Haines-Young and Potschin 2018) and widely used in several scientific projects: ESMERALDA (Geneletti et al. 2020), MAIA (Nedkov et al. 2022), and SELINA (Pereira et al. 2024).

According to CICES (Haines-Young and Potschin 2018), ES are grouped into three sections: (i) provisioning, (ii) regulation and maintenance, and (iii) cultural. Regulating ecosystem services (RES), as a category of ES, relies on all functions through which ecosystems and inhabited living organisms affect the environment surrounding humans, to ensure health and well-being (Haines-Young and Potschin 2018). Flood regulation, alongside regulation of the chemical composition of the atmosphere and oceans and regulation of temperature and humidity, including ventilation and transpiration, are the key RES in cities (Maes et al. 2016; Stoycheva and Geneletti 2023).

The EU's Nature Restoration Law (NRL) (Regulation 2024/1991) describes RES as the most essential ES in urban ecosystems. RES in urban ecosystems are characterised by increased demand and low supply, as they are mainly provided by UGI.

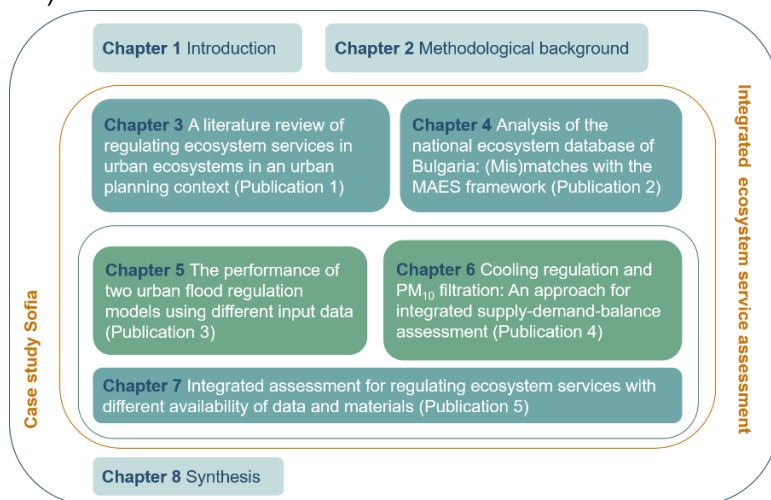
## 1.2. Objective and research tasks

The primary objective of this thesis is to develop a methodological approach for the integrated assessment of regulating ecosystem

services in urban areas. Following the thesis research question on how to develop a methodological approach for integrated assessment of urban regulating ecosystem services, the following tasks were performed:

1. Literature review for identification of the priority regulating ecosystem services in urban areas and methods for their assessment, modelling and mapping.
2. Analysis and assessment of the applicability of models and datasets for mapping and assessment of the regulating ecosystem services in urban areas.
3. Development of an approach for individual ecosystem service supply, demand and balance assessment.
4. Development of an integrated approach for urban regulating ecosystem services assessment at multiple tiers.

Following the state-of-the-art and the identified research tasks, we have constructed an overall framework, which presents the place of each research publication (chapter) within the thesis (Fig. 1.1).

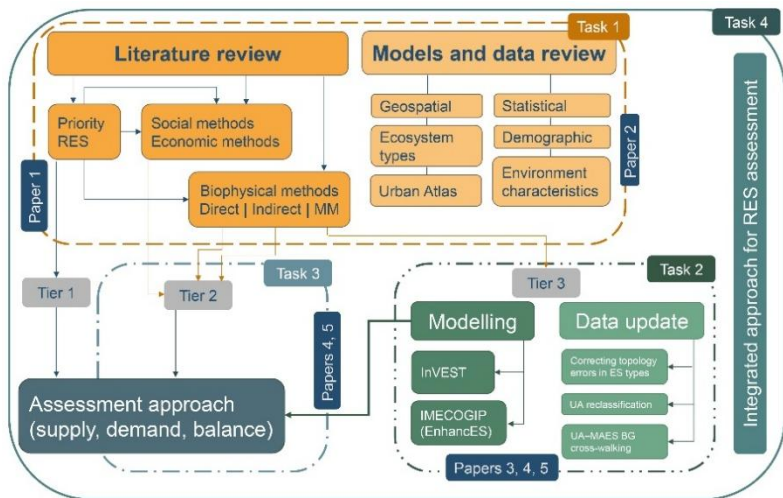


**Figure 1.1.** The overall framework of the thesis. Further details are available in Chapter 2.

## Chapter 2: Methodological background

### 2.1. Conceptual framework

The conceptual framework (Fig. 2.1) represents the thesis workflow and how each of the papers is implemented in the whole study. It follows four main tasks integrated into five publications. The first task includes the state-of-the-art review of the regulating ecosystem services (RES), models and data review (Chapters 3, 4).



**Figure 2.1.** Conceptual framework of the integrated approach for regulating ecosystem service assessment.

Task 2 includes the two subtasks—modelling and data update. Several processes were performed for the case study datasets, and the land use/land cover (LULC) was updated. Further cross-walking with the national ecosystem database was performed. The modelling subtask includes the study, preparation, and testing of the available collected datasets for the case study. We have used two ES-based models—InVEST and the EnhancES toolbox (previously

IMECOGIP) with some of their modules for specific RES assessment.

Task 3 includes the assessment of ecosystem service (ES) supply, demand and balance. We have proposed the improvement of previously used approaches for ES supply, demand and balance assessment. The proposed approach assesses the RES supply through data modelling, whereas for the demand assessment, a composite index of vulnerability, exposure and hazard indicators has been used. We have further applied geospatial analyses for vulnerable areas identification (Optimized Hot Spot Analysis and Optimized Outlier Analysis). Results of the research from task 3 have been applied in Chapters 5, 6 and 7.

Task 4 encompasses and improves the previously developed approach for the RES assessment of six priority ES for Sofia within the integrated ecosystem service assessment framework. We have used the multi-tiered approach for the ES supply-demand assessment, as several constraints applied to the models (lack of modules for their assessment), dataset limitations and uncertainties. This task includes the research that encompasses the thesis and has been applied in Chapter 7.

## 2.2. Case study

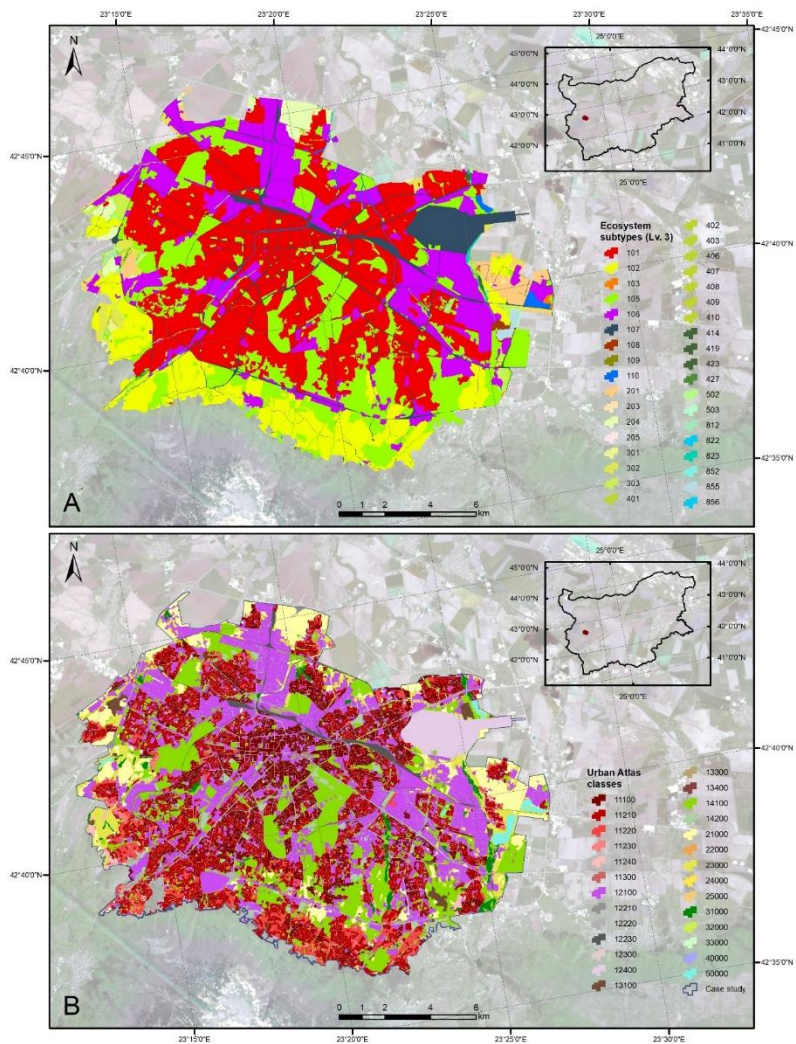
Sofia is the capital city and the biggest urban area in Bulgaria. The case study area of Sofia is located in the western part of Bulgaria and covers an area of 221.53 km<sup>2</sup> (Fig. 2.2) and has been studied as part of the INES project (Petkova et al. 2022).

Sofia's case study reflects the spatial extent of the impact of the densely urbanized area. The borders of the case study follow the extent of the urban heat island intensity in the 20–22 h interval (August 2019) (Sofiaplan 2020b) and the boundaries were corrected according to the extent of the polygons of the ecosystem types from the national methodologies for Mapping and Assessment of Ecosystems and their Services in Bulgaria (MAES BG) (Bratanova-Doncheva et al. 2017). The ecosystem types in Bulgaria have been

mapped by using several projects following the MAES framework (Maes et al. 2013). They cover eight terrestrial ecosystems and one marine ecosystem (Bratanova-Doncheva et al. 2017). Mapping was performed for the entire country, except for the NATURA 2000 zones.

The case study presents six out of eight terrestrial ecosystem types from the MAES classification (Maes et al. 2013) (Fig. 2.2A). They include urban, cropland, grassland, woodland and forests, heathland and shrub, and freshwater ecosystems. Urban ecosystems are the predominant type presented by all ten subtypes developed for Bulgaria according to the methodology for urban ecosystems (Zhiyanski et al. 2017). The largest proportion has J1. Residential and public areas; J5. Urban green areas (incl. sport and leisure facilities); J6. Industrial sites (incl. commercial sites); and J7. Transport networks and other constructed hard surfaced sites.

To compare and evaluate the models' performance using different input data (Chapter 5), we also used the classes from the Urban Atlas dataset (EEA 2020), while performing additional analyses and cross-walking between the Urban Atlas database (version 2018), ecosystem types, and the newly added classes for urban green infrastructure from the Sofiaplan (2020b).



**Figure 2.2.** Case study area. **A** Ecosystem subtypes (Level 3, 2017) **B** Urban Atlas classes (2018).

## 2.3. Task 1: Literature review for identification of the priority regulating ecosystem services in urban areas and methods for their assessment, modelling and mapping

### 2.3.1. Literature review

The literature review (Chapter 3) was performed following the international experience for conducting a literature review. The selection of literature was based on a search performed within the international databases Scopus and Web of Science (WoS). The following operation for extracting data was organised into a table template and included a set of different characteristics, both for ecosystem services, methods, as well as the used dataset and its characteristics. The identified RES from the review were also identified within the unpublished methodology for mapping and biophysical assessment of the state of ecosystems and the services they provide for application in territorial and spatial planning in Sofia Municipality (Sofiaplan 2020a). The Methodology identifies 12 priority ES, six of which are regulating (Table 1).

**Table 1.** Priority regulating ecosystem services identified by Sofiaplan and studied in the thesis (based on Sofiaplan 2020a).

| Priority ES                | CICES 5.1 class                                                                              | CICE<br>S 5.1<br>code | CICE<br>S 4.1<br>code | Review<br>paper<br>RES<br>(%) |
|----------------------------|----------------------------------------------------------------------------------------------|-----------------------|-----------------------|-------------------------------|
| Contamination purification | Bio-remediation by micro-organisms, algae, plants, and animals                               | 2.1.1.1               |                       | 1.72                          |
|                            | Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals | 2.1.1.2               |                       | 29.31                         |
| Noise and other            | Smell reduction                                                                              | 2.1.2.1               |                       | 1.72                          |

|                              |                                                                                                |         |                 |       |
|------------------------------|------------------------------------------------------------------------------------------------|---------|-----------------|-------|
| nuisance attenuation         | Noise attenuation                                                                              | 2.1.2.2 |                 | 18.97 |
|                              | Visual screening                                                                               | 2.1.2.3 |                 | 5.17  |
| Flood protection             | Hydrological cycle and water flow regulation (Including flood control, and coastal protection) | 2.2.1.3 | 2.2.2.2/2.2.2.1 | 62.07 |
| Pollination and biodiversity | Pollination (or 'gamete' dispersal in a marine context)                                        | 2.2.2.1 | 2.3.1.1         | 13.79 |
|                              | Seed dispersal                                                                                 | 2.2.2.2 | 2.3.1.1         | 3.45  |
| Pest and disease control     | Pest control (including invasive species)                                                      | 2.2.3.1 | 2.3.2.1         | 5.17  |
|                              | Disease control                                                                                | 2.2.3.2 | 2.3.2.2         | 8.62  |
| Climate regulation           | Regulation of chemical composition of atmosphere and oceans                                    | 2.2.6.1 | 2.3.5.1         | 75.86 |
|                              | Regulation of temperature and humidity, including ventilation and transpiration                | 2.2.6.2 | 2.3.5.2         | 70.69 |

### 2.3.2. Models and data review

In parallel with the literature review, a data review was made, based on the main findings from the review (used models and their input data), as well as geospatial data for the case study, including ecosystem types and Urban Atlas, identified as available and open-source datasets, as well as used in the review publications.

#### 2.3.2.1. InVEST

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model is one of the most used models for ES assessment (Natural Capital Project 2023). The model was initially released in 2011 with ten modules for mapping and assessing goods and services from nature (Natural Capital Project 2011). Specifically, the dedicated module for flood-related ES assessment in an urban

environment is the Urban Flood Risk Mitigation (UFRM) module, released later on, in 2020 (Natural Capital Project 2020). The UFRM has been widely applied to case studies in different countries and geographical scales (Cortinovis et al. 2022).

#### *2.3.2.2. EnhancES (IMECOGIP)*

The IMECOGIP toolbox was developed under the “Implementation of the ecosystem services framework in green infrastructure planning for resilient urban development in the Ruhr and in Chinese megacities” (IMECOGIP) project (Ruhr-Universität Bochum, Geogr. Institut 2021). The model is an open GIS-based toolbox (QGIS) for ES assessment and trade-off evaluation for different urban environments, consisting of six different modules for regulating ES (Alpha Release, IMECOGIP 2021). Afterwards, the model was renamed to EnhancES, the IMECOGIP Toolbox ES model, and the number of covered ecosystem services increased to three provisioning, 11 regulating and six cultural (IMECOGIP 2024; Zepp et al. 2025).

For all three used models, an additional Preprocessing model needed to be run before running the actual ecosystem service-specific module (IMECOGIP 2024). The tool is used for dataset homogenization, especially for land use, extension and quality check. The input dataset includes the Area of Interest (AOI) and Land Use as mandatory datasets, and Individual Soil Information (Available Water Capacity (nFK), Groundwater Level (GW) and Soil Information) as not mandatory datasets (IMECOGIP 2024).

For the flood regulation supply (CICES 2.2.1.3 Hydrological cycle and water flow regulation (Including flood control, and coastal protection)), we have used IMECOGIP's module CICES 2.2.1.3: Waterflow Regulation (Retention Model) (WRRM), which is designed to model individual heavy rain events (Ruhr-Universität Bochum, Geogr. Institut 2021) to calculate the runoff avoidance capacity of a case study area. For a full description of the Retention Model, input datasets and output results, its application and

comparison with the InVEST Urban Flood Risk Mitigation module, please refer to Chapter 5.

For the 2.1.1.2 Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals (PM<sub>10</sub> filtration), we have used EnhancES CICES 2.1.1.2a: Mediation of traffic-caused pollution (PM<sub>10</sub>-Tool). The model assesses the PM<sub>10</sub> filtration supply as the capacity of vegetation cover to reduce PM<sub>10</sub> pollution, which is caused by traffic (IMECOGIP 2024; Zepp et al. 2025).

The CICES 2.2.6.2 Regulation of temperature and humidity, including ventilation and transpiration, or further referred to as cooling regulation, we have used the EnhancES CICES 2.2.6.2: Temperature Regulation (Cooling Intensity – ET), which assesses the quantitative dimensions of temperature regulation as cooling intensity (Zepp et al. 2025). The cooling intensity is based on the understanding of air temperature reduction of green area units (LULC) compared to the grey infrastructure (sealed infrastructure) (Zepp et al. 2025). In the result layer, the temperature regulation is calculated as the reduced temperature (in Kelvin) of vegetation-dominated LULC class (based on the FAO's grass reference evapotranspiration), compared to impervious surfaces (Zepp et al. 2025). The model also uses the initial soil water condition and crop coefficient.

## 2.4. Task 2: Analysis and assessment of the applicability of models and datasets for mapping and assessment of the regulating ecosystem services in urban areas

### 2.4.1 Data analysis and update

The analysis of the available datasets gives an overview of the need for improvement and updating. This update of the geospatial dataset includes an update to the ecosystem types database and the Urban Atlas datasets.

#### 2.4.1.1. Ecosystem types update

The ecosystem types covering the case study area from the different layers were merged into a single shapefile. After performing a topology analysis, hundreds of errors were discovered (815 overlaps and 336 gaps). They included overlapping (Table 2) between two or more ecosystem types and subtypes and gaps between different ecosystem features.

**Table 2.** Number of identified overlaps between ecosystem types within the case study area (Petkova et al. 2022).

| Ecosystem type      | Ecosystem type      | Overlap errors |
|---------------------|---------------------|----------------|
| Cropland            | Grassland           | 24             |
| Cropland            | Heathland and shrub | 1              |
| Cropland            | Woodland and forest | 8              |
| Grassland           | Woodland and forest | 36             |
| Heathland and shrub | Grassland           | 18             |
| Heathland and shrub | Freshwater          | 4              |
| Heathland and shrub | Woodland and forest | 24             |
| Urban               | Cropland            | 55             |
| Urban               | Heathland and shrub | 56             |
| Urban               | Freshwater          | 26             |
| Urban               | Woodland and forest | 563            |
| <b>Sum</b>          |                     | <b>815</b>     |

#### 2.4.1.2. Urban Atlas update

The Urban Atlas update approach consisted of several stages of geospatial data correction of the datasets. These included changing the polygon classes and adding new classes (and subclasses: levels 3 and 4). Class changes were performed using a different approach based on the specifics of each class. All classes were compared with the ecosystem subtypes and then reclassified based

on the ecosystem subtypes and orthophoto interpretations of the area.

#### *2.4.1.3. Further improvement of the green infrastructure*

UA dataset was further improved with the Sofiaplan dataset by adding green infrastructure classes (Sofiaplan 2020b). The UGI was divided into 16 categories, which cover 48% of the case study (the largest area occupied the “Green area in discontinuous urban fabric” and “Ruderal vegetation”).

#### *2.4.2 Analysis of the models' applicability for ES supply*

The models' applicability analysis is always performed for a specific purpose, in this case, for the ES supply. The analysis of the models' applicability was achieved by comparing several aspects of the models (InVEST and IMECOGIP/EnhancES). A key part of the comparison was using the same input dataset of single events, as well as with time series of events (rainfall with return periods of 20, 100 and 1000 years).

### *2.5. Task 3: Development of an approach for individual ecosystem service supply, demand and balance assessment*

The composed approach consists of three groups of steps, based on the assessment of the (i) supply, (ii) demand and (iii) balance of each urban regulating ecosystem service. The geospatial analyses are performed for the identification of priority areas for each urban regulating ecosystem service. They are performed in both GIS software (ArcGIS Map 10.6, ArcGIS Pro 3.6.4 and QGIS) and statistical software (MS Excel, geospatial statistics in ArcGIS Pro 3.6.4).

## 2.5.1. Ecosystem service supply

### 2.5.1.1. Model data and modelling (InVEST, IMECOGIP/EnhancES)

In this study, we follow the conceptual background of the supply, as defined by Burkhard et al. (2012), as supply is the capacity of an area to provide a number of ecosystem goods and services for a specific time period. Following this understanding, the ES supply was assessed by using two urban-specific ES assessment models: InVEST and IMECOGIP/EnhancES.

### 2.5.1.2. Statistical analyses

#### A. Normalization (0–1 scale)

The normalization is a pre-step for the geospatial analysis, and it is performed to enable comparison between different models and tools (Patro and Sahu 2015). This is needed as different models have different parameter outputs, and their comparability should be ensured. We have used the min-max normalization method (Patro and Sahu, 2015), which is calculated as (Equation 1):

$$Normalization(x) = (x - x_{min}) / (x_{max} - x_{min}) \text{ (Eq. 1)}$$

Where *Normalization(x)* is the normalized cell/feature output; *x* is the single input of the raster cell of the dataset and/or the polygon feature of the dataset; *x<sub>min</sub>* and *x<sub>max</sub>* are the minimum and maximum values of the raster cell of the dataset and/or the polygon feature of the dataset.

#### B. Area-weighted mean value

For the provision of specific values for each LULC class, we calculated area-weighted mean values for each of the assessments (supply, demand, balance).

## 2.5.2. Ecosystem service demand

Following the definition by Burkhard et al. (2012), the ES demand refers to the sum of all ecosystem goods and services, which are consumed or used in a specific area for a defined time period. As

most of the previous RES assessments have been focusing on the supply assessment, the demand and resulting balance, trade-offs, synergies and disservices have been less studied (Yao et al. 2021; Stoycheva and Geneletti 2023; Kowalska et al. 2024). With the aim of expanding the ES research on the demand assessment availability, we have modified the approach proposed by Morabito et al. (2015) and applied by Popov et al. (2019) for heat-related risk assessment. This approach was applied to two ES—cooling regulation and PM<sub>10</sub> filtration (Chapter 6). For assessing each individual demand, we have integrated two sets of indicators: 1) vulnerability and exposure composite index, and 2) hazard index.

#### *2.5.2.1. Vulnerability and exposure composite index*

The vulnerability index (VI), proposed as the heat vulnerability index by Li and Sun (2023), was modified to the case study data availability. The index encompasses demographic and socio-economic indicators (Li and Sun 2023). The adapted index includes:

- 1) the percentage of the population above 65 years old (NSI 2023),
- 2) the percentage of the population under 14 years old (NSI 2023),
- 3) the percentage of the female population (NSI 2023),
- 4) the percentage of the population below high school education level (UfS 2023), and
- 5) the average monthly income of the population (Sofiaplan 2017).

All datasets were calculated per administrative region and then normalised from 0 to 1 to compose the VI. The VI is weighted to 50% of the combined vulnerability and exposure layer.

The exposure index (EI) (Morabito et al. 2015; Popov et al. 2019) consists of the population density (NSI 2023) for each administrative region of the case study, and it is weighted to 50% of the combined vulnerability and exposure layer. Both vulnerability index and

exposure index were used for the demand assessment of cooling regulation and PM<sub>10</sub> filtration (Chapter 6).

#### 2.5.2.2. Hazard index

We have used two approaches for assessing the hazard indices for cooling regulation and PM<sub>10</sub> filtration ES (Chapter 6). Following the approaches for PM<sub>10</sub> filtration suggested by Baró et al. (2015), Amini Parsa et al. (2019), and Yao et al. (2021), we have adapted them to the case study of Sofia. The PM<sub>10</sub> filtration hazard index was calculated as a function of the maximum concentrations of the PM<sub>10</sub> and the average yearly PM<sub>10</sub> values (Equation 2):

$$ESd = EQS - AMV \text{ (Eq. 2)}$$

Where: *ESd* is the ecosystem demand, *AMV* is the average yearly PM<sub>10</sub> values; *EQS* (environmental quality standards) is the maximum concentration of PM<sub>10</sub> (average yearly concentration no more than 40 µg/m<sup>3</sup>) (European Commission 2015).

The cooling regulation hazard index was derived from the cooling regulation intensity (intensity of the UHI) (Sofiaplan 2020c).

#### 2.5.3. Balance

The balance was assessed as the mismatches between the ES supply and demand. In our case, the ES balance was calculated following Equation 3:

$$Balance = Supply - Demand \text{ (Eq. 3)}$$

##### 2.5.3.1. Geospatial analyses

The spatial relations of geographical data are characterised and analysed through spatial autocorrelation analyses (Isola et al. 2025). Spatial autocorrelation includes global and local spatial correlation (Yu and Ma 2025). In Chapters 6 and 7, we have used the local spatial correlation analysis, as implemented in Optimized Hot Spot Analysis (Getis-Ord Gi\*) and the Optimized Outlier Analysis (Anselin Local Moran's I) tools in ArcGIS Pro software (ArcGIS Pro 2025a, 2025b) for analysing the clustering and spatial outliers of the ES balance in the study area.

#### A. Optimized Hot Spot Analysis (Getis-Ord Gi\*)

Optimized Hot Spot analysis is used for the identification of hot spots (spatial clusters of high values) and cold spots (spatial clusters of low values) of ES provision (ArcGIS Pro 2025a). The analysis is performed for ES assessments in Chapters 6 and Chapter 7.

#### B. Optimized Outlier Analysis (Anselin Local Moran's I)

This step is performed as a step for further improving the results from the Optimized Hot Spot Analysis and analysing the spatial relations between the different RES. The Optimized Outlier Analysis allows assessing the clustering of statistically significant high (hot spots) and low (cold spots) values, as well as high and low clusters/outliers within the ES data (ArcGIS Pro 2025a). The results of the analyses could be interpreted as ES synergies (high-high and low-low clustering) and ES trade-offs (high-low and low-high outlying) (Yu and Ma 2025).

### 2.6. Task 4: Development of an integrated approach for urban regulating ecosystem services assessment at multiple tiers

Although the advancement of urban data generation is increasing (Kwon et al. 2023), the data availability and its application are still issues, which reduce the potential for complex assessment of ecosystems and the services they provide. The data availability is directly influencing the methods used for ecosystem service assessment (Nedkov et al. 2022). This is related to data quality, time series, and the extent of the datasets. Following these limitations on the data availability, we have selected the multi-tiered approach for assessing the six priority regulating ecosystem services for Sofia.

We have followed the multi-tiered approach for mapping and assessing the natural heritage potential for the needs of the ecosystem service assessment proposed by Nedkov et al. (2022). We have modified the approach for the urban environment, based

on the data and their quality. As a first step, the integrated ecosystem service assessment has been developed and applied as a pilot for two out of six ES—cooling regulation and PM<sub>10</sub> filtration at tier 3 (Chapter 6). The completely developed approach is further applied for all six priority regulating ES in Sofia (Sofiaplan 2020b), based on the data availability, uncertainties of the available datasets and the time constraints.

The multi-tiered approach consists of three tiers (levels) of the available data and their actual usage as an indicator for ES assessment. The first tier is used for not centralised datasets, which results in the usage of expert assessment for the specific ES indicators. Tier 2 consists of statistical or biophysical datasets at the municipality level, but not spatially explicit. They are further refined and used in the geospatial analyses. Tier 3 encompasses the most detailed data and methods used for the ES assessment—modelling methods.

For this research, we have selected six priority RES: air purification (PM<sub>10</sub> filtration, 2.1.1.2), noise attenuation (2.1.2.2), flood regulation (2.2.1.3), pollination (2.2.2.1), pest control (2.2.3.1) and cooling regulation (2.2.6.2). Their ES supply and demand are assessed following the data availability and their uncertainties. The supply of noise attenuation and pest control was assessed at tier 1, whereas at tier 1, demand was assessed for pollination and pest control. Noise attenuation (demand) and pollination (supply) were assessed at tier 2. PM<sub>10</sub> filtration, flood regulation, and cooling regulation were assessed at tier 3 for both supply and demand.

### **Chapter 3: A review of regulating ecosystem services in the context of urban planning**

The results of this chapter are published in: Stoycheva V, Geneletti D (2023) A review of regulating ecosystem services in the context of urban planning. Journal of the Bulgarian Geographical Society 48: 27-42. <https://doi.org/10.3897/jbgs.e93499>

## **Abstract**

There is a high growing demand for regulating ecosystem services such as air quality regulation, regulation of air temperature and humidity, and flood regulation, in urban ecosystems which is important for urban planning. A comprehensive review of the current studies of the urban ecosystem, regulating ecosystem services, and their connection with urban planning actions is needed. The current paper presents such a review conducted in six stages to evaluate the state-of-the-art of regulating ecosystem services and their relationship with urban planning. It includes 58 papers selected after a precise keywords search and developed by publication screening, defining indicators, developing an assessment template, and meta-analysis of the results. The analyses are focused on spatial data used in the studies, the methods applied for ecosystem services assessment, and the relationships between regulating ecosystem services, urban planning, and green infrastructure. The most studied regulating ecosystem services within reviewed publications are *regulation of chemical composition of atmosphere and oceans, regulation of temperature and humidity, including ventilation and transpiration, and hydrological cycle and water flow regulation (including flood control, and coastal protection)*. Although urban planning-related papers are only 1/3 of the pool of papers, appropriate results have been obtained for assessing the urban planning-regulating ecosystem services relation. The review also identified some significant knowledge gaps that can be used as a starting point for future studies.

## **Introduction**

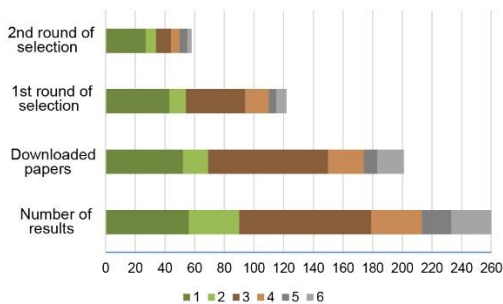
As one of the most needed ecosystem services (ESs) in urban ecosystems, regulating ecosystem services (RESs) need detailed studying. Following the existing scientific research on the problems of RESs, the main objective of this study is to provide systematic information on RESs in urban ecosystems from UP's perspective,

as well as to better understand linkages with green infrastructure (GI), and methods used for their assessment.

## Methodology

A literature review was performed to evaluate the state of the art of RES and its correlation with urban planning and green infrastructure topic (Fig. 3.1):

1. selection of keywords;
2. identification of publications;
3. first round of screening – a combination of keywords;
4. second round of screening (abstract screening);
5. full-text screening based on eligibility criteria;
6. content analysis of included publications.

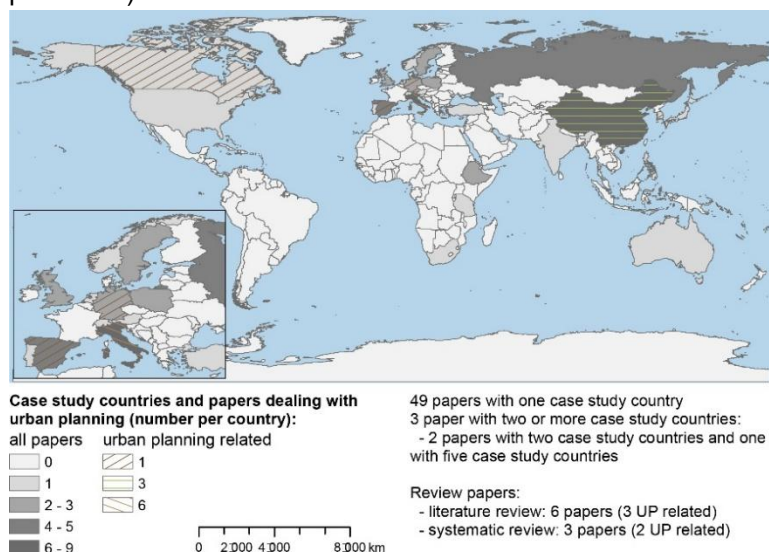


**Fig. 3.1.** Number of papers per keywords searches (1–6) on every stage.

## Results

All 58 papers have a case study in 25 countries (Fig. 3.2). For a better understanding of RESs, a detailed evaluation of the used assessment methods was performed (Fig. 3.3). UP-related papers show a relationship between direct measurement methods and modelling methods and suggest good UP-related practices, as well as principles for territorial management. The most studied RESs within reviewed publications are regulation of chemical composition of atmosphere and oceans, regulation of temperature and humidity, including ventilation and transpiration, and hydrological cycle and

water flow regulation (including flood control, and coastal protection).



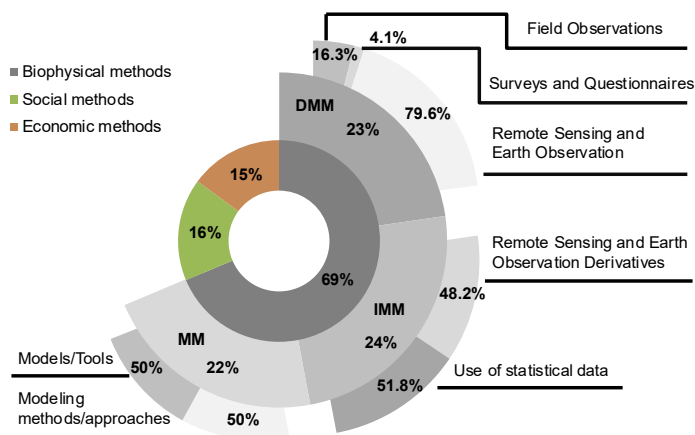
**Figure 3.2.** Map of the case study countries and papers dealing with urban planning.

## Discussion

As one of the main aims of this study, a review of the relationship amongst RES, green infrastructure and urban planning, was performed. Urban planning has been studied in only 29% of all reviewed papers, which represents the identified knowledge gap in studies both assessing ES and defining their urban planning implementation. The majority of urban planning-related papers studied 2.2.1.3, 2.2.6.1 and 2.2.6.2 at the same time and give examples for urban planning practices implementation. The other implementation tool is principles for territorial management, which is used in papers studying all three main ES, as well as other RES.

Biophysical assessment methods are the most used for RES assessment due to the use of remote sensing and Earth observation data, which is up-to-date and give opportunities for updating

ecosystem changes. There is no acknowledgeable implementation of social and economic methods in ES assessment in reviewed studies, as they cannot be used as a substitute for biophysical ones (Castillo-Eguskitza et al. 2019).



**Figure 3.3.** RESs assessment methods. Inner circle – biophysical, social, and economic methods. Middle circle – types of biophysical methods: Direct Measurement Methods (DMM), Indirect Measurement Methods (IMM), Modeling Methods (MM). Outer circle: types of DMM, IMM, and MM.

## Conclusion

The scientific interest in the relationships amongst urban ecosystem services, assessment methods and urban planning is growing. As a main group of ecosystem service in urban ecosystems, regulating ecosystem services combine interdisciplinary studies in defining and resolving urban challenges. A strong relationship is found in the papers studying bundles of RES (although usually they are not defined as singles) all at the same time at a city-scale level of 30 m or more, whereas regulation of chemical composition of atmosphere and oceans (2.2.6.1) is mostly assessed at a city region-scale and ES regulation of temperature and humidity, including ventilation and

transpiration (2.2.6.2) is predominantly studied at a city-scale level in LULC spatial units with a resolution of 10-30 m.

The study results show significant use of biophysical methods for RES assessment in urban areas. Economic and social methods are also used alone or in combination with biophysical methods, but their presence is relatively small. This is an identified gap in the ES assessment concept, as the overall RES assessment should use an interdisciplinary approach and a combination of assessment methods. There is an equal distribution within biophysical methods which shows the broad range of used assessment methods. Although remote sensing and Earth observation-related methods and models are the most preferred by authors as they give an empirical result to each study and can be correlated with other results from similar studies.

## **Chapter 4: Analysis of the national ecosystem database of Bulgaria: (Mis)matches with the MAES framework**

The results of this chapter are published in: Petkova G, Prodanova H, Stoycheva V (2022) Analysis of the national ecosystem database of Bulgaria: (Mis)matches with the MAES framework. Journal of the Bulgarian Geographical Society 47: 73-82. <https://doi.org/10.3897/jbgs.e99268>

### **Abstract**

The mapping of ecosystems is a significant element in the European Biodiversity Strategy and the results of its implementation should support the maintenance and restoration of ecosystems and their services. The quality of the spatial data is of crucial importance for the achievement of these goals. A methodological framework for Bulgaria in the form of nine separate methodologies has been developed in recent years. In this paper, we analyze the ecosystem typology for Bulgaria and the GIS database to assess the possibilities to develop a common database for the needs of

integrated water management. The data analyses were carried out in two dimensions: 1) the typology and attributive data were analyzed by cross-tabular approach; and 2) the spatial data were analyzed by topology rules. The results of the study reveal three main problems of the typology: 1) for some types it is developed to the fourth level while for others it is to the third level; 2) in some of the ecosystem types, especially in the freshwater ecosystems, different categories are mixed within a single hierarchical level; 3: there are duplicated numerical designations between grassland and forest ecosystems. This necessitates a revision of the typology and the development of a correct uniform classification to be used for the needs of integrated assessment. The topology analyses of the merged data from the eight ecosystem GIS layers show extremely large numbers of gaps and overlaps. The main reason is the use of different sources for the mapping of different ecosystem types. The main conclusion is that it is practically impossible to generate topologically correct integrated GIS layers from the eight ecosystem type layers. Therefore, it is necessary to develop a new approach for mapping all ecosystem types into a uniform database.

## **Introduction**

The mapping of ecosystems is a significant element in the European Biodiversity Strategy which sets a target to EU member states to map and assess the state of ecosystems and their services in their national territory. A methodological framework for mapping and assessment of ecosystems and the services they provide has been developed under the MetEcosMap project (Methodological assistance for ecosystem assessment and biophysical valuation). It includes nine separate methodologies (Bratanova-Doncheva et al. 2017) each of which covers a specific ecosystem type according to the MAES typology. Based on these methodologies, an assessment and mapping by ecosystem types was performed for the territories of the country falling outside the NATURA 2000 network. The analyses of the ecosystem types are performed in two case studies

representative for the terrestrial ecosystems in the country: the Ogosta river basin and the city of Sofia. The database contains data for nine ecosystem types found in the country. The case studies cover eight of them excluding the marine ecosystems.

### **Database analyses**

The data analyses were carried out in two dimensions: 1) the attributive data and the classification itself, published in the methodologies, were checked including its hierarchical levels, their names, and the separation criteria; and 2) the spatial data was reviewed - geometry, the presence of gaps and overlaps between the 8 layers and between the graphical elements within them. A primary check in Excel and GIS revealed several mismatches in general related to certain ecosystem types, the most significant of which are related to woodland and forest, grassland, and freshwater ecosystems. Problematic areas requiring correction were removed and missing information was completed. The detection and removal of the errors and inconsistency of spatial data in vectors are the main concerns of the Geographic Information Systems (GIS). In the current work we used two main topology rules to analyze the quality of the ecosystem database: must not overlap and must not have gaps.

#### **(Mis)matches in the typology and attributes' data**

Several mismatches were identified: duplicate numerical designations between grassland and woodland and forest ecosystems; mismatches between the forest ecosystems classified in the Bulgarian methodology and those in the MAES framework; mismatches between codes and names of freshwater ecosystems classified in the Bulgarian methodology and those in the MAES framework; mismatches between Bulgarian MAES and EUNIS.

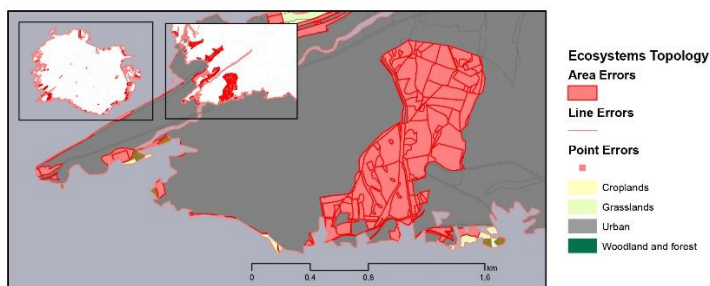
#### **(Mis)matches in spatial data**

The topology analyses of the spatial data are performed using ArcGIS software. The analyzes are made for both case studies, the Ogosta river basin and the urban part of the city of Sofia. The results

are generated in two formats: 1) statistics in tabular format, and 2) spatial vector data (polygon and linear objects representing the gaps and overlaps of the data).

There is about 80% data coverage of the basin. The rest of the area falls within the NATURA 2000 network which was outside of the national ecosystem mapping. The topology data analysis carried out for the Ogosta river basin area identified more than 57 000 gaps and overlaps. The cropland, grassland, heathland and shrub ecosystem types have the most frequent errors in the data.

The results from the topology analyses of the city of Sofia show the predominant number of errors located in the periphery of the case study (Fig. 4.1). The main reason for this spatial distribution is the fact that the same areas appear as boundaries between urban ecosystems and other subtypes, e.g. grassland or cropland. The most frequent errors are between urban, cropland, or heathland and shrub overlapping any of the other types (Table 1). Urban ecosystems have the largest overall proportion of overlaps, with a total of 700 errors, of which only 563 errors are between urban and woodland and forest ecosystem types.



**Figure 4.1.** Close-up view of the gaps and overlaps between selected ecosystem types in the data for the city of Sofia.

## Conclusions and future steps

The topology analyses of the merged data from the eight ecosystem GIS layers show extremely large numbers of gaps and overlaps. The main reason is in the use of different sources for the mapping

of different ecosystem types. Therefore, it is necessary to develop a new approach for mapping of all ecosystem types into a uniform database. This source can be used to develop an initial spatial dataset of the ecosystem types at level 2.

## **Chapter 5: The performance of two urban flood regulation models using different input data**

The results of this chapter are published in: Stoycheva V, Nedkov S (2024) The performance of two urban flood regulation models using different input data. One Ecosystem 9: e134022. <https://doi.org/10.3897/oneeco.9.e134022>

### **Abstract**

Increasing climate change has led to an increase in urban flood events. Events with a return period of twenty years become events with a period of two to three years. The primary objectives of this study are to evaluate the performance of flood regulation models using different input data and compare their performance for flood regulation supply (FRS) assessment. The assessment of the ecosystem services of urban FRS was performed using two models: Urban Flood Risk Mitigation (UFRM) by Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) and IMECOGIP Waterflow Regulation (Retention Model) (WRRM). They rely on relatively accessible open-source data, require a short time to model each scenario and provide opportunities to interpret results in different spatial and measurement units. We performed several improvements to the input data, including updating the national ecosystem-type assessment for the case study area by connecting it with the Urban Atlas typology and proposing an approach for soil data refinement. The outputs of the two models show significant differences in FRS values for each land-use/land-cover (LULC) class. The UFRM assesses different impervious urban classes with different values, varying from very low to medium. In contrast, the WRRM assesses the FRS in densely sealed areas with one fixed

value for low supply (where nearly all rainfall is transformed into runoff).

## **Introduction**

Floods are amongst the primary impacts of climate change (UN DESA 2022), leading to widespread losses and damage to cities, settlements and infrastructure in highly dense urban ecosystems (IPCC 2023). Flood regulation mapping and assessment can provide the necessary data to define the flood mitigation capacity of different areas and, thus, contribute to effective urban planning related to flood risk reduction. The flood regulation ES is based on the function of the ecosystems to retain a part of the incoming rainwater in cases of flood events (Nedkov and Burkhard 2012).

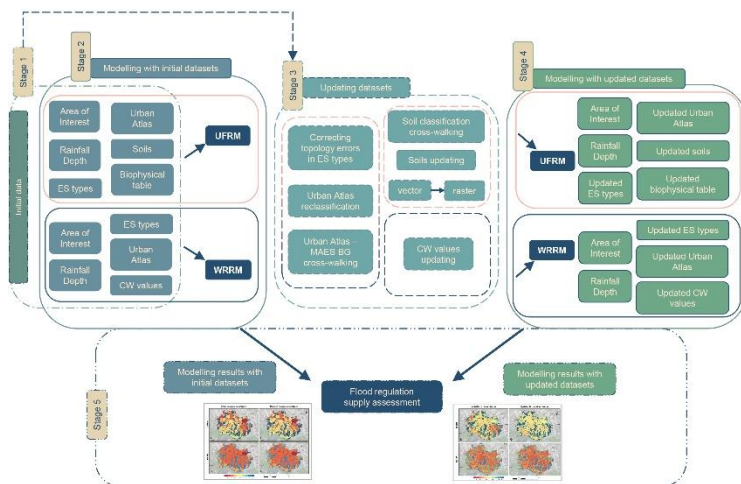
Flood regulation, as one of the most crucial and frequently studied ES, is an integral part of many ES models/tools. The Urban Flood Risk Mitigation (UFRM) model of InVEST and CICES 2.2.1.3: Waterflow Regulation (Retention Model) (WRRM), which is part of the IMECOGIP toolbox, are two models that ensure appropriate means for flood regulation assessment that can be highly useful for urban planning purposes. Both UFRM and WRRM quantify the effect of pluvial floods.

In this study, we applied two open-source ES models, InVEST UFRM and IMECOGIP WRRM, to quantify FRS in urban ecosystems, based on the city of Sofia, Bulgaria as a case study for pluvial floods. The primary objectives of this study are to evaluate the performance of the models using different input data and compare their usage for FRS assessment. The specific tasks were as follows:

1. collect the available free input data;
2. execute the models with the available input data;
3. update the quality of the input data;
4. execute the models with updated data and
5. assess the FRS based on different inputs.

## Materials and methods

We developed a specific five-stage approach to assess the performance of the two models, based on different inputs, which enables the execution of models with different input data and comparative analyses of the results (Fig. 5.1). The first stage consisted of collecting and analysing all available and applicable data for the case study area, as well as studying the two models and their characteristics. In the second stage, the models were executed using the initial datasets. The next stage involved updating the initial datasets to improve their quality. The improvement in quality and accuracy was performed for the model input data—soil types, ecosystem types datasets and Urban Atlas classes by updating the already existing datasets and applying an approach for soil types update. Stage 4 included new modelling with already updated datasets and the final stage was data analysis and FRS assessment.



**Figure 5.1.** Conceptual scheme of the proposed approach.

UFRM—InVEST Urban Flood Risk Mitigation; WRRM—IMECOGIP CICES 2.2.1.3: Waterflow Regulation (Retention Model); CW—Discharge

coefficient; MAES BG—Mapping and Assessment of Ecosystems and their Services in Bulgaria.

Both models used similar sets of input data; however, their outputs are relatively different. There is a difference in the LULC datasets because the UFRM requires a raster layer, whereas the WRRM requires a vector layer. For UFRM, there are no restrictions on the use of different classifications because users can define their specific classifications for the case study area. On the contrary, WRRM requires the LULC classes to be adapted to the sample data provided in the toolbox or own datasets with CW values have to be provided.

### **Data update**

All the datasets have limitations and shortcomings that reflect the manner in which they have been developed. Improvement in the initial data may lead to more precise and accurate modelling results. Adjustment of the CN based on the imperviousness was made for the artificial Urban Atlas datasets. This follows the suggested by Vallecillo et al. (2020) approach for refinement of the Urban Atlas dataset (which is derived from the Corine Land Cover). We have used the following equation (4):

$$CN_{Total} = 98 \times \left(\frac{Imp}{100}\right) + \left(1 - \frac{Imp}{100}\right) \times CN_{CLC} \text{ (Eq. 4)}$$

Where Imp is the level of imperviousness (soil sealing) and CN (in our case UA) is the CN derived from Vallecillo et al. (2020) without correction.

### **Flood regulation modelling (InVEST Urban Flood Risk Mitigation and IMECOGIP)**

The InVEST UFRM calculates the runoff retention per pixel of the LULC layer (Natural Capital Project 2023) (Table 3). We executed the model with different input data, simulating different scenarios, as follows: three precipitation depths, ecosystem subtypes as LULC (initial and updated), Urban Atlas classes as LULC (initial and

updated), soils (initial and updated) and the required input data of the biophysical table for each of the LULC scenarios.

The IMECOGIP WRRM (Table 3) is designed to model individual heavy rain events (Ruhr-Universität Bochum, Geogr. Institut 2021) to calculate the runoff avoidance capacity of a case study area.

**Table 3.** Correspondence of the outputs between InVEST UFRM and IMECOGIP WRRM. \* Outputs used for analysis

| InVEST UFRM                                                                                                                                                                                                                                                                                                                                                            |                          | IMECOGIP WRRM                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                     |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|
| Outputs                                                                                                                                                                                                                                                                                                                                                                | Type                     | Outputs                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Type                                |
| Parameter log                                                                                                                                                                                                                                                                                                                                                          | text (.txt)              | No similarity                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                     |
| Runoff retention                                                                                                                                                                                                                                                                                                                                                       | raster (no unit)         | Partial similarity                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                     |
| Runoff retention                                                                                                                                                                                                                                                                                                                                                       | raster (m <sup>3</sup> ) | No similarity                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                     |
| Runoff values                                                                                                                                                                                                                                                                                                                                                          | raster (mm)              | No similarity                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                     |
| Flood risk service:<br>- rnf_rt_idx*: average of runoff retention values per watershed;<br>- rnf_rt_m3: sum of runoff retention volumes in m <sup>3</sup> per watershed;<br>- flood_vol: the flood volume per watershed;<br>- aff_bld: potential damage to built infrastructure in currency units per watershed;<br>serv_blt: service built values for this watershed. | vector<br>(permanent)    | Cw Values<br>- CW value*: multiplier/factor: 0 avoid runoff to 1 full runoff;<br>- Area (A): m <sup>2</sup> ;<br>- P (mm): precipitation intensity (mm = l/m <sup>2</sup> );<br>- R_R (km <sup>2</sup> ): Present-Retention Situation of avoid runoff;<br>- R_R_gew (%): Present-Retention Situation area weighted;<br>- F_R (km <sup>2</sup> ): Best Retention case (whole area is forest CW = 0.15 and CW = 1 for water bodies);<br>- F_R_gew (%): Best Retention case (Forest Retention) area weighted;<br>- W_R (km <sup>2</sup> ): Worst Retention case (whole area is sealed surface CW = 0.9); | vector<br>(temporary and permanent) |
| -                                                                                                                                                                                                                                                                                                                                                                      |                          | ES Balance: a standardized scale (0 to                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | vector<br>(temporary)               |

|                                                                             |                   |
|-----------------------------------------------------------------------------|-------------------|
| 1) showing the deficit in<br>ES supply compared to<br>the ideal conditions. | and<br>permanent) |
|-----------------------------------------------------------------------------|-------------------|

## Results

The InVEST UFRM outputs include three runoff retention parameters representing the amount of precipitation captured per grid cell (Table 4). Runoff values varied between 0 (no retention) and 69 mm (the entire amount of precipitation captured by the ecosystem). For the runoff retention parameters, these values are transformed into quantities ( $m^3$ ) and relative retention capacities ranging from zero to one. The latter was defined as the most appropriate to depict the spatial distribution of runoff retention and was used for further analyses of the FRS. These outputs provide the option for estimating the FRS of each ecosystem subtype and Urban Atlas classes.

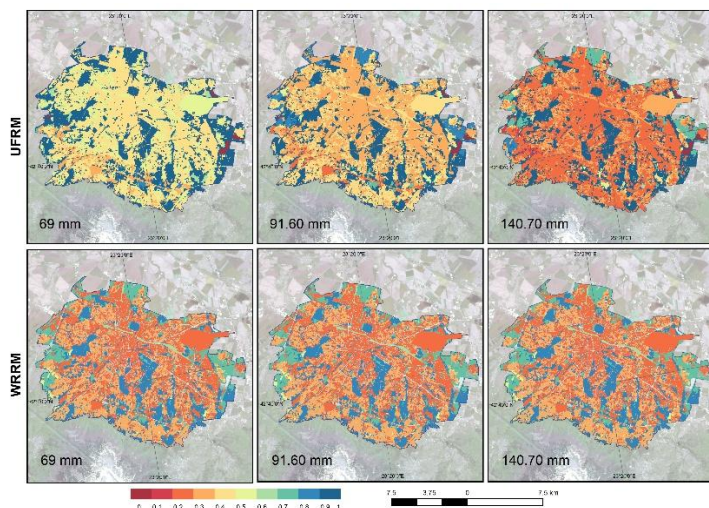
The two models have different results when used for a series of rainfall events. The UFRM shows changes in its output, especially the FRS values for different classes, whereas the WRRM did not adapt its FRS values for each rainfall scenario, which results in preserving the same values for all modelled events, regarding different precipitation depths. The FRS values of the two models were highly diverse (Fig. 5.2). This is a result of the input data, which included only LULC and CW values.

## Discussion

The soil characteristics (including their initial water conditions) could affect the flood regulation potential of the ecosystems (Zepp et al. 2023). The UFRM requirement of soil data and their incorporation in the modelling process ensure more precise results of flood regulation assessment, in comparison to the WRRM.

A common limitation of both models is the lack of inclusion of the specific topography of the area (e.g. elevation, slopes), referring to the lack of relief input data in both models. The inclusion of such elements in the model can serve as a second round of verification

of the model outputs (if we interpret the soils as the first). The other suggested by Vallecillo et al. (2020) improvement that we applied includes the adjustment of the CN values by the percentage of imperviousness for each LULC class. This adjustment enables the differentiation of the artificial classes (sealed) and refining the CN number.



**Figure 5.2.** FRS based on different precipitation depth scenarios.

## Conclusions

The study demonstrates how the improvement of input data reduces the uncertainties of modelling results. This approach is an objective trade-off between data accuracy, accessibility of datasets and relevant adaptation to the local characteristics of the case study area.

## Chapter 6: Cooling regulation and PM<sub>10</sub> filtration: An approach for integrated supply-demand-balance assessment (Under review)

The results of this chapter are submitted to: Stoycheva V, Nedkov S (2026) Cooling regulation and PM<sub>10</sub> filtration: An approach for

integrated supply-demand-balance assessment. Urban Climate (Under review).

## **Abstract**

Following the increased needs in the urban ecosystem services (ES) provision, the main objective of the present study is to propose a GIS-based approach for supply-demand-balance assessment of cooling regulation and PM<sub>10</sub> filtration in urban ecosystems, and to examine how the selected regulating ES are spatially related. The study uses cooling regulation as a proxy for local climate regulation and PM<sub>10</sub> filtration as a proxy for air purification, which could provide appropriate and spatially explicit indicators for assessing the capacity of urban green areas to support human well-being and environmental quality within urban ecosystems. The supply is assessed through an ES biophysical modelling using EnhancES, the IMECOGIP Toolbox model. The proposed GIS-based modelling approach for demand assessment integrates risk and hazard indexes, as well as geospatial and statistical analyses for identifying vulnerable areas. Land use/land cover (LULC) classes can produce a positive or negative balance, depending on their geographical location, and different ES values within hot spots, cold spots, spatial clusters and outliers. For the case study of Sofia, Bulgaria, the PM<sub>10</sub> filtration has a higher share in the formation of the combined negative balance than the cooling regulation, which is a result of the combined high demand (population-induced) on this ES, as well as relatively low supply from all of the LULC classes, especially the green areas. Additionally, during a heatwave, small green areas within the urban fabric cannot provide sufficient cooling regulation.

## **Introduction**

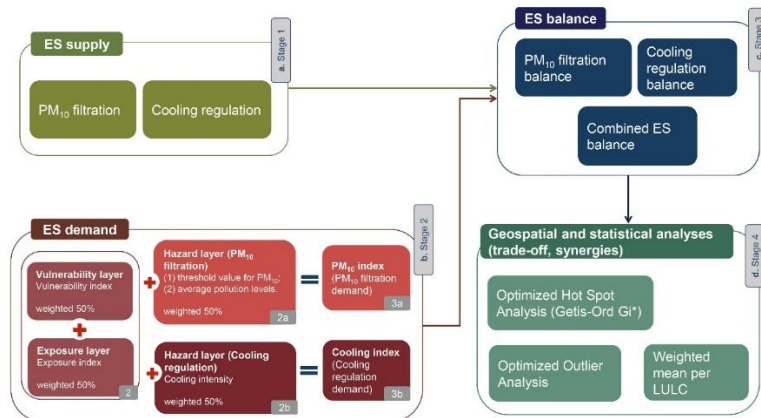
The urban green infrastructure provides a variety of regulating ES, and some of them, such as air purification and local climate regulation, are closely related to human health. Therefore, selecting appropriate indicators and focusing on specific aspects of the services is necessary to ensure reliable and applicable analyses. In

this respect, cooling regulation as a proxy for local climate regulation and PM<sub>10</sub> filtration as a proxy for air purification could provide appropriate and spatially explicit indicators for assessing the capacity of urban GI to support human well-being and environmental quality within urban ecosystems.

The main objective of the current study is to propose a GIS-based approach for supply-demand-balance assessment of cooling regulation and PM<sub>10</sub> filtration in urban ecosystems. More specifically, the study aims to (i) identify the spatial distribution of supply and demand areas for these services; (ii) examine the spatial interrelationships between them; and (iii) determine whether these interactions result in synergies or trade-offs within the urban environment.

## Methods

The proposed methodological approach consists of four stages (Fig. 6.1): ES supply assessment (Stage 1), ES demand assessment (Stage 2), ES balance assessment (Stage 3), and Geospatial and statistical analyses (trade-offs and synergies) (Stage 4).



**Figure 6.1.** Conceptual scheme of the methodological framework.

The first stage (supply assessment) encompasses the ES biophysical modelling using EnhancES, the IMECOGIP Toolbox ES model (IMECOGIP 2024). The ES, following the CICES 5.1 (Haines-Young and Potschin 2018), are 2.2.6.2 Regulation of temperature and humidity, including ventilation and transpiration (cooling regulation) and 2.1.1.2 Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals (PM<sub>10</sub> filtration). The PM<sub>10</sub> filtration model calculates the capacity of vegetation cover to mediate PM<sub>10</sub> pollution caused by traffic. The model derives the potential PM<sub>10</sub> pollution reduction based on the monthly mean PM<sub>10</sub> concentration. Cooling regulation (CICES 2.2.6.2: Temperature Regulation (Cooling Intensity – ET) assesses the temperature regulation as the cooling intensity of vegetation (as part of LULC) during heatwaves, as a result of the plant evapotranspiration. The resulting layer calculates the reduced temperature (in Kelvin) of vegetation-dominated LULC, compared to impervious surfaces (Zepp et al. 2025).

The second stage (Fig. 6.1) consists of ES demand assessment, based on the approach proposed by Morabito et al. (2015) and applied by Popov et al. (2019) for calculating a heat-related risk index. The approach was modified to reflect the local characteristics of the case study, and the resulting demand indices, comprising exposure and vulnerability components, which were adapted separately for each of the two services.

The vulnerability index (VI), used in both ES assessments, was modified after Li and Sun (2023) to refine the demand of the study. The adapted index includes 1) the percentage of the population above 65 years old, 2) the percentage of the population under 14 years old, 3) the percentage of the female population, 4) the percentage of the population below high school education level, and 5) the average monthly income of the population. All datasets were calculated per administrative region and then normalised from 0 to 1 to compose the VI. The second common index between the two

ES is the exposure index (EI). It consists of the population density for each administrative region of the case study.

The second main composing indicator for the demand indices is the hazard indices. We have assessed the PM<sub>10</sub> regulation demand by adjusting the approach proposed and applied by Baró et al. (2015), Amini Parsa et al. (2019), and Yao et al. (2021) for our case study area characteristics and data availability.

The ES balance, trade-off and synergies are calculated using further geospatial analysis in GIS (ArcGIS and QGIS) and statistical analyses in MS Excel. The geospatial analyses include Optimized Hot Spot analysis (Getis-Ord Gi\*) and Optimized Outlier Analysis (Anselin Local Moran's I).

## **Results**

The supply of PM<sub>10</sub> filtration and cooling capacity (Fig. 6.2) follows the urban green area LULC classes. The average temperature reduction by green infrastructure follows a similar trend, except for blue infrastructure, which has a higher average temperature reduction. The classes with the lowest cooling capacity supply are 11310 (0.0), 11210 (0.03) and 12100 (0.04).

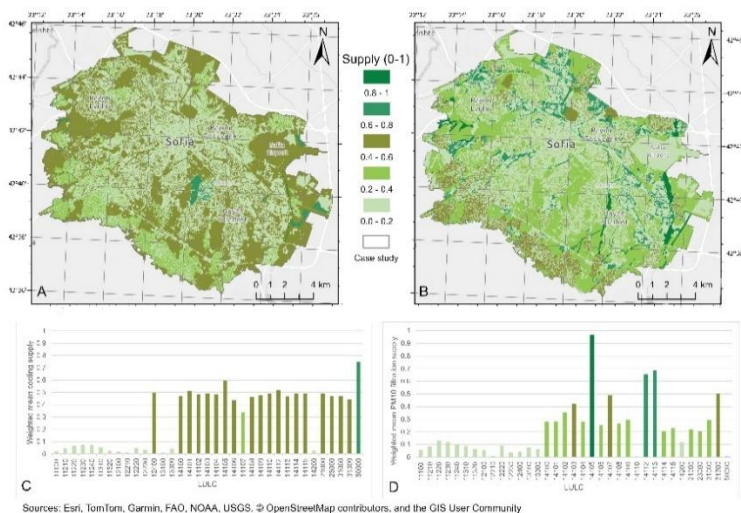
The demand for the two ES was calculated as a function of the exposure and vulnerability indices. The cooling demand (Fig. 6.3) for the case study is 0.52, as the highest demand has the administrative regions of Lyulin, Mladost, and Vazrazhdane. The mean PM<sub>10</sub> filtration demand for the study area is 0.51 (Fig. 5b), as the average demand per LULC does not have a significant difference between each class.

The ES balance of cooling regulation (Fig. 6.3) and PM<sub>10</sub> filtration shows similar trends in the case study area. Relatively small areas of the case study have a positive balance (the supply is larger than the demand). These areas mainly cover green and blue infrastructure. The sealed areas, especially for the PM<sub>10</sub> filtration, have a low balance (-0.4). There is a significant difference between the balance values per LULC within cold spots (predominantly

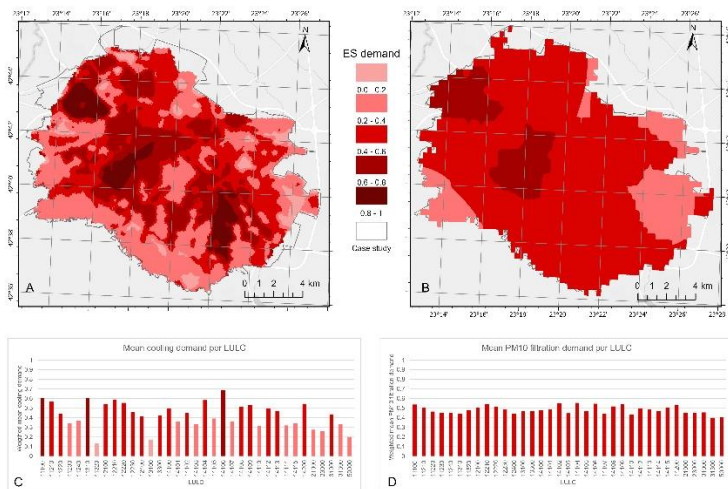
negative balance), hot spots (rarely positive balance values) and the weighted balance value for the case study (regarding of cold spots, hot spots or not significant relations). The analyses of green areas within cold spots of ES balance (Fig. 6.4) suggest a strong geospatial connection between each of the spots (clusters with negative balance). On the other hand, such a connection does not apply to the green infrastructure elements – Borisova Garden, which is isolated from the other GI elements. The exceptions include the natural GI classes of riparian woodland (14105), the vegetation from the cemetery class (14103), and the green area in discontinuous urban fabric (14107) in the Vitosha mountain foothills.

## Discussion

This approach utilises GIS-based analyses and can be applied to various geographical scales. The implementation of this approach enables an integrated ES assessment for climate regulation and PM<sub>10</sub> filtration, and the identification of the specific hot/cold spots.



**Figure 6.2.** Ecosystem service supply. (a) Cooling capacity supply, (b) PM<sub>10</sub> filtration supply, (c) Mean cooling supply per LULC, (d) Mean PM<sub>10</sub> filtration supply per LULC.

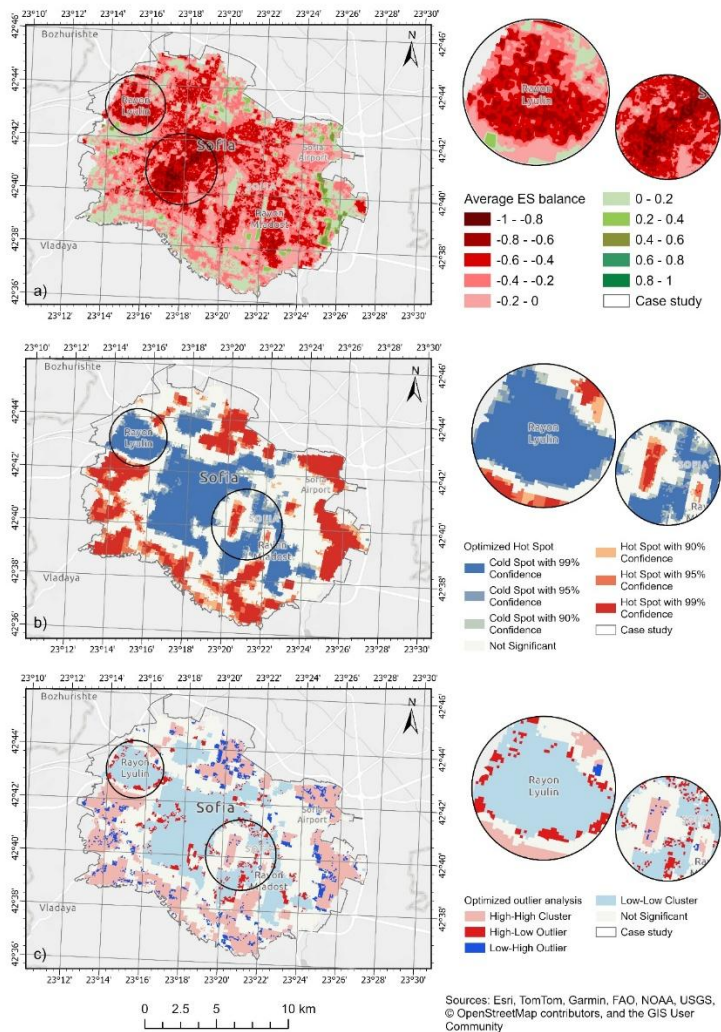


Source: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

**Figure 6.3.** ES Demand. (a) Cooling demand, (b) PM<sub>10</sub> filtration demand, (c) weighted mean cooling demand per LULC, and (d) weighted mean PM<sub>10</sub> filtration demand per LULC.

## Conclusions

This study proposes a GIS-based modelling approach for an integrated ecosystem service assessment for supply-demand-balance for cooling regulation and PM<sub>10</sub> filtration, and further identification of areas with significant importance (vulnerable areas) for the combined ES provision (hot spots and outlier analyses). The results reveal that the cooling regulation has relatively higher average ES supply values, and the green areas LULC classes have closely related values. The demand for PM<sub>10</sub> filtration is higher than that for cooling regulation.



**Figure 6.4.** Cooling and PM<sub>10</sub> filtration balance (combined) spatial analyses for: (a) ES balance, (b) Optimized hot spot analysis, and (c) Optimized outlier analysis.

## **Chapter 7: A multi-tiered approach for integrated assessment of regulating ecosystem services: A case study of Sofia, Bulgaria**

The results of this chapter are submitted to: Stoycheva V, Nedkov S (2026) A multi-tiered approach for integrated assessment of regulating ecosystem services: A case study of Sofia, Bulgaria. *Acta geographica Slovenica* (Submitted).

### **Abstract**

This study aims to assess the geospatial distribution of six priority regulating ecosystem services for the urban areas of Sofia, the capital city of Bulgaria. We have used the multi-tiered approach for the ecosystem service (ES) assessment, following the data availability and applicability, as the studied ES include air purification, noise attenuation, flood regulation, pollination, pest control, and local climate regulation. Each ES was assessed for supply, demand, balance and geospatial analyses were applied for the identification of clustering areas with high or low ES provisioning. Nevertheless, the demand of each ES has higher values, and several areas overlap; the ES supply areas are more distinctive. High relations were identified for local climate regulation and air filtration, as well as pest control and noise attenuation, whereas the non-significant for the ES of pollination and local climate regulation and pollination and air filtration. Although the study has limitations regarding the modelling and expert-based assessment, the proposed approach for ES assessment with limited data may be integrated into planning practices.

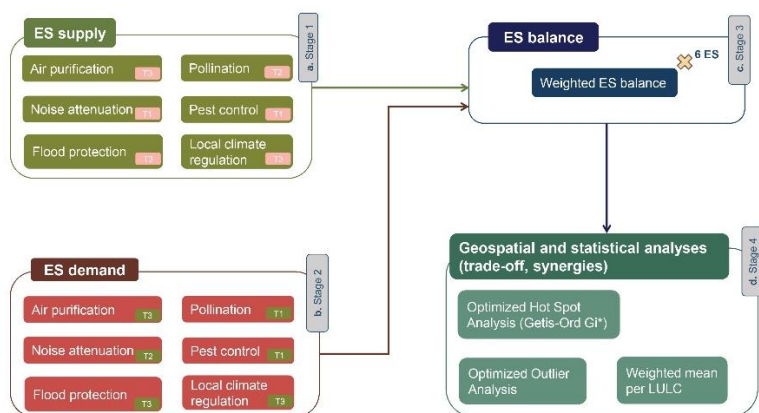
### **Introduction**

The urban RES have been quantified via different assessment approaches. The majority of the studies rely only on the supply provision (Stoycheva and Geneletti 2023; Kowalska et al. 2024), whereas the demand is not included or quantified as the population-derived needs.

The main objective of this research is to propose an integrated ecosystem service assessment for urban regulating ecosystem service assessment. We aim specifically at: (i) constructing an integrated ES assessment approach for multiple tiers; (ii) identifying the spatial distribution of ES supply and demand; (iii) analysing the spatial interrelationships between the ES.

## Methods

The methodological approach applied for this research integrates the multi-tiered approach suggested by Nedkov et al. (2022) and the supply-demand-balance assessment approach (Stoycheva and Nedkov 2026a) (Fig. 7.1) and includes four stages: 1) ES supply assessment; 2) ES demand assessment; 3) ES balance assessment; 4) geospatial and statistical analyses.



**Figure 7.1.** Methodological approach for ecosystem service assessment.

This study assesses six groups of regulating ecosystem services (RES) (Table 1), which include 1) air purification, 2) noise attenuation, 3) flood regulation, 4) pollination, 5) pest control, and 6) local climate regulation. These RES are selected following the review of ES with relation to urban planning (Stoycheva and Genelleti 2023), and also identified within the unpublished

methodology for mapping and biophysical assessment of the state of ecosystems and the services they provide for application in territorial and spatial planning in Sofia Municipality (Sofiaplan 2020a).

**Table 1.** Priority regulating ecosystem services, tiers, and models used for their assessment. (Stat. = analyses of statistical data; mun. = municipality).

| Priorit<br>y ES          | CICES<br>class                                                                                                               | 5.1   | Tier<br>(sup<br>ply) | ES assessment<br>approach<br>(supply)                                                                                                             | Tier<br>(dema<br>nd) | ES<br>assessment<br>approach<br>(demand) |
|--------------------------|------------------------------------------------------------------------------------------------------------------------------|-------|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|------------------------------------------|
| Air<br>purifi<br>cation  | 2.1.1.2<br>Filtration/seque<br>stration/storage<br>/accumulation<br>by micro-<br>organisms,<br>algae, plants,<br>and animals |       | 3                    | EnhancES<br>CICES 2.1.1.2a:<br>Mediation of<br>traffic-caused<br>pollution (PM10-<br>Tool)                                                        | 3                    | Spatial<br>proxy                         |
| Noise<br>atten<br>uation | 2.1.2.2 Noise<br>attenuation                                                                                                 | Noise | 1                    | Expert<br>assessment                                                                                                                              | 2                    | Stat.<br>data/mun.                       |
| Flood<br>regul<br>ation  | 2.2.1.3<br>Hydrological<br>cycle and water<br>flow regulation<br>(Including flood<br>control, and<br>coastal<br>protection)  |       | 3                    | 1) InVEST<br>Urban Flood<br>Risk Mitigation<br><br>2) IMECOGIP<br>(EnhancES)<br>CICES 2.2.1.3:<br>Waterflow<br>Regulation<br>(Retention<br>Model) | 3                    | Spatial<br>proxy                         |
| Pollin<br>ation          | 2.2.2.1<br>Pollination (or<br>'gamete'<br>dispersal in a<br>marine context)                                                  |       | 2                    | Spatial proxy                                                                                                                                     | 1                    | Expert<br>assessment                     |
| Pest<br>contr<br>ol      | 2.2.3.1<br>Pest<br>control<br>(including<br>invasive<br>species)                                                             |       | 1                    | Expert<br>assessment                                                                                                                              | 1                    | Expert<br>assessment                     |

| Priorit<br>y ES                        | CICES<br>class                                                                                            | 5.1 | Tier<br>(sup<br>ply) | ES assessment<br>approach<br>(supply)                                                  | Tier<br>(dema<br>nd) | ES<br>assessment<br>approach<br>(demand) |
|----------------------------------------|-----------------------------------------------------------------------------------------------------------|-----|----------------------|----------------------------------------------------------------------------------------|----------------------|------------------------------------------|
| Local<br>climat<br>e<br>regul<br>ation | 2.2.6.2<br>Regulation of<br>temperature<br>and humidity,<br>including<br>ventilation and<br>transpiration |     | 3                    | EnhancES<br>CICES 2.2.6.2:<br>Temperature<br>Regulation<br>(Cooling<br>Intensity - ET) | 3                    | Spatial<br>proxy                         |

The air purification supply is based on the findings of Stoycheva and Nedkov (2026a), which were assessed with the EnhancES toolbox module CICES 2.1.1.2a: Mediation of traffic-caused pollution (PM<sub>10</sub>-Tool). The noise attenuation supply assessment is based on the functional characteristics of the urban green infrastructure: vegetation size, structure, and density, and it is applied at tier 1 (expert assessment). The flood regulation supply was assessed as a scenario of the updated Urban Atlas dataset for the high-probability event of 20-year rainfall frequency occurrence (Stoycheva and Nedkov 2024) with the module CICES 2.2.1.3: Waterflow Regulation (Retention Model) (WRRM). Pollination supply is assessed at tier 2 with a spatial proxy, which includes the beehives location and bee foraging radius. The ES of pest control (including invasive species) (2.2.3.1) is assessed at tier 1 (expert assessment). The local climate regulation supply is based on the findings of Stoycheva and Nedkov (2026a), which were assessed with the EnhancES toolbox module CICES 2.2.6.2: Temperature Regulation (Cooling Intensity – ET).

The ES demand assessment for the six priority ES was done on tier 1, 2 and 3, based on the data availability, applicability and time constraints. For pollination and pest control ES, we have used expert assessment (tier 1). Noise attenuation was assessed at tier 2, with a spatial proxy, and for the ES of cooling regulation, PM<sub>10</sub> filtration and flood regulation, we have used the modified approach

(Stoycheva and Nedkov 2026a) integrating risk (vulnerability and exposure) and hazard indices (tier 3).

The final results of the balance, with equal weight for both ES, were derived from Equation 5:

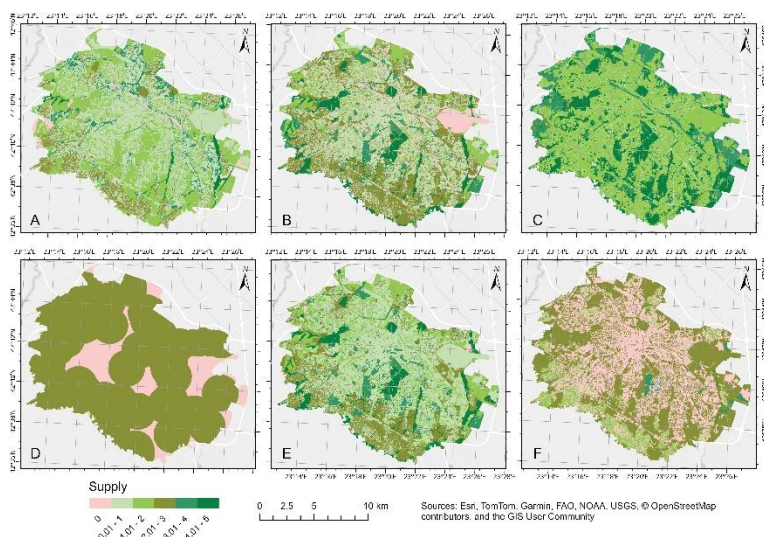
$$\text{Balance} = (\text{Balance}_{(\text{Air purification})} + \text{Balance}_{(\text{Noise attenuation})} + \text{Balance}_{(\text{Flood regulation})} + \text{Balance}_{(\text{Pollination})} + \text{Balance}_{(\text{Pest control})} + \text{Balance}_{(\text{cooling regulation})}) / 6 \text{ (Eq. 5)}$$

In this study, we have used the Optimized Hot Spot Analysis (Getis-Ord Gi\*) and Optimized Outlier Analysis (Anselin Local Moran's I). Throughout the Hot Spot Analysis, we have analysed the spatial correlation, including spatial clusters with high (hot spots) and low (cold spots) values. We have interpreted them as ecosystem service synergies (high-high and low-low clustering) and ecosystem service trade-offs (high-low and low-high outlying) (Yu and Ma 2025).

## Results

Ecosystem service supply has been assessed individually for all six priority ES (Fig. 7.2). The highest overall capacity is pollination (3.00), whereas the lowest is the local climate regulation supply (1.64). Overall, the ES assessed at tier 3 had a lower mean supply for the case study. The air purification supply (Fig. 7.2A) has a low capacity supply for almost all LULC classes, although some of the UGI classes have medium capacity, 14103 Cemetery (2.99), 14107 Green area in discontinuous urban fabric (2.77) and 31300 Coniferous woodlands (2.71). The noise attenuation (Fig. 7.2B) has been assessed with the clear distinction of the UGI. The highest values are applied to the LULC classes with less anthropogenic influence, such as 14101 Urban forest and 14105 Riparian woodlands. The flood regulation supply (Fig. 7.2C) has a relatively vast distribution of the ES values. The highest values apply to the UGI classes, 14100 Urban green areas (5), 31300 Forests (5), as well as the blue infrastructure of 50000 Water bodies (5). The

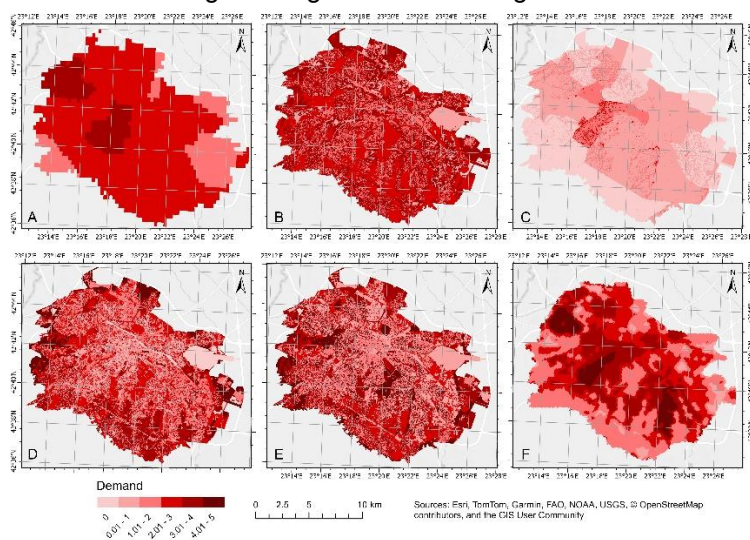
pollination supply (Fig. 7.2D) has the highest values for the UGI, as well as for some of the residential classes (11210 Discontinuous Medium Density Urban Fabric (S.L.: 30% - 50%)), where the green area coverage could be a source of the supply for bee foraging. Pest control supply (Fig. 7.2E) follows the UGI with natural potential for providing the service, especially for UGI with a close-to-natural state.



**Figure 7.2.** Ecosystem service supply. **A** Air purification **B** noise attenuation **C** flood regulation **D** pollination **E** pest control **F** local climate regulation.

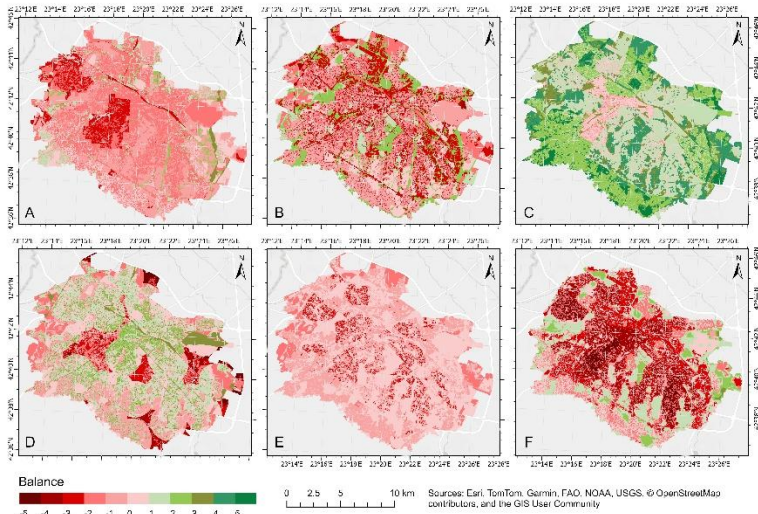
Ecosystem service demand has high values for every ESW, except for flood regulation (Fig. 7.3). Air purification demand (Fig. 7.3Aa) is characterised by overall medium values for the case study and higher values for four of the districts—Lyulin and parts of Vazrazhdane, Krasno selo and Triaditsa. The noise attenuation demand (Fig. 7.3B) is based on the assessment at tier 2, and the highest demand has been applied to all transportation LULC classes (12210, 12220), as well as for some of the areas experiencing high noise demand, such as 12100 Industrial,

commercial, public, military and private units. The flood regulation demand (Fig. 7.3C) has a low demand value (0.77 mean) and is relatively equally distributed. The pollination demand (Fig. 7.3D) is characterised mainly by the high values for the natural or semi-natural areas of arable lands, pastures and some of the UGI classes (14104 Urban garden), as closely needing the pollination service. The ES demand for pest control has a similar functional pattern as the pollination demand (Fig. 7.3E). The most deprived areas include natural and semi-natural classes, such as 14101 Urban forest, 14105 Riparian woodland, etc., which have a high pressure from the local population and the possibilities for introducing new invasive species. Local climate regulation demand (Fig. 7.3F) has one of the highest demand values (2.95), as the build-up classes, such as 11100 and 11210, have the highest mean values, as a result of excessive building coverage and soil sealing.



**Figure 7.3.** Ecosystem service demand. Ecosystem service supply. **A** Air purification **B** noise attenuation **C** flood regulation **D** pollination **E** pest control **F** local climate regulation.

The overall balance (Fig. 7.4) for five out of six ES is negative, except for flood regulation (1.97 mean).

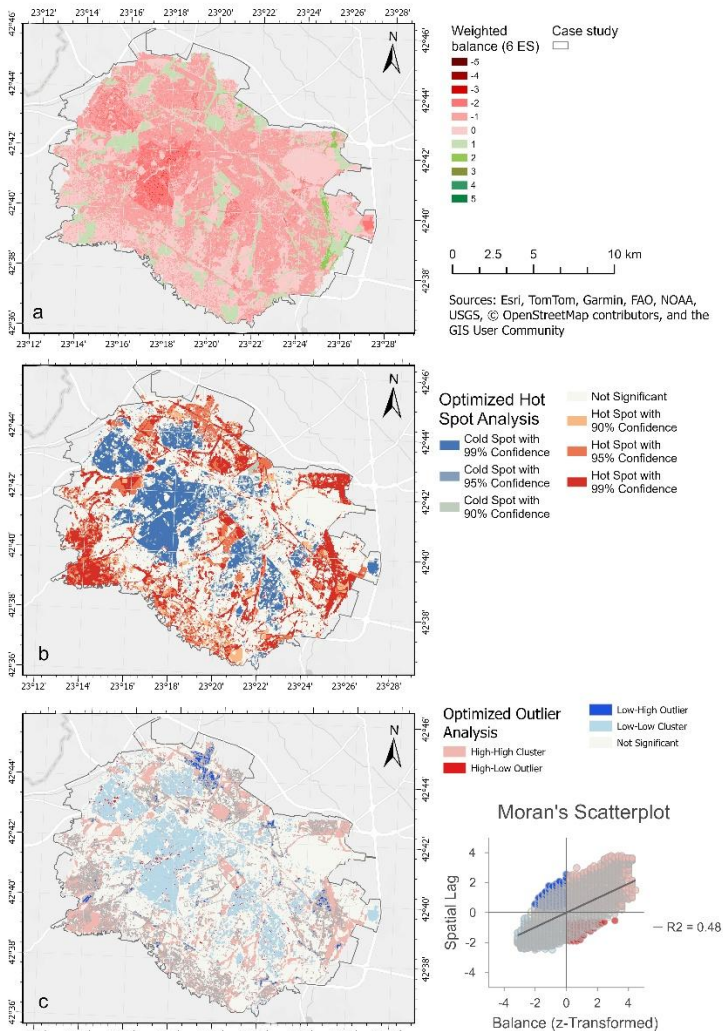


**Figure 7.4.** Ecosystem service balance. **A** Air purification **B** noise attenuation **C** flood regulation **D** pollination **E** pest control **F** local climate regulation.

Spatial interrelations between ecosystem services are present within the clustering of positive or negative values (Fig. 7.5). The positive balance applies to some of the UGI classes, such as 14105 Riparian woodland, 14103 Cemetery, and 14101 Urban forest. Whereas the UGI class of 14106 Green area in continuous urban fabric has highly negative values (-1.14).

## Discussion

The applied approach has limitations, similar to other ES approaches, such as related to the LULC datasets, application of the matrix approach and expert assessment. Through the approach identifying and addressing the most vulnerable and deprived areas is performed, based on the ES supply, demand, trade-offs and synergies.



**Figure 7.5.** Geospatial analyses. **A** Weighted ecosystem service balance for all six ES **B** Optimized Hot Spot Analysis of the weighted ecosystem service balance for all six ES **C** Optimized Outlier Analysis of the weighted ecosystem service balance for all six ES.

## **Conclusions**

The study proposes a multi-tiered approach for an integrated ecosystem service assessment for supply-demand-balance for six priority ecosystem services: air purification, noise attenuation, flood regulation, pollination, pest control, and local climate regulation. Vulnerable areas with combined ES provision (hot spots and outlier analyses) were further identified. The suggested approach is based on different data sources, available datasets for ES assessment and data quality and applicability.

## **Chapter 8: Synthesis**

### **8.1. Main results and answers to the objective and research tasks**

Following the main research question on how to develop a methodological approach for integrated assessment of urban regulating ecosystem services, the thesis demonstrates the developed approach through which the priority regulating ecosystem services for the case study are assessed. The literature review (Chapter 3) identified high-priority regulating ecosystem services, which are later connected with the identified ones from the local authorities and are further assessed in Chapters 4–7. The results of Chapter 5 showcase the differences in the applied ES models and the potential influence of the used datasets on the models' outputs. The integrated approach for the ES assessment is being piloted for two ES—cooling regulation and PM<sub>10</sub> filtration (Chapter 6), and adapting a demand approach is being implemented. The main results refer to the data availability and its implementation for ES assessment. As a result, a multi-tiered approach was applied for all six priority regulating ecosystem services, based on the data availability, data uncertainty and time constraints.

### 8.1.1. Literature review for identification of the priority RES in urban areas and methods for their assessment, modelling and mapping

As RES are identified as the most essential ecosystem services in urban ecosystems, their main sources of provision should also be thoroughly studied. For urban environments, these are urban green infrastructure (green and blue infrastructure elements). Following these dynamics of the urban RES-related topic, we have performed a literature review for the identification of the priority RES, which we have integrated into a multi-tiered assessment at a later stage (Chapters 5–7). These results align with the identified by IPBES direct drivers of changes for biodiversity and ES, which have their realisation in urban areas via extreme heat events, floods, pollution, introduced invasive alien species and land use changes. The identified research gaps on ecosystem demand, trade-offs and synergies were addressed in the construction of the individual and integrated approaches for ES supply-demand-balance assessment and their further interrelations.

### 8.1.2. Analysis and assessment of the applicability of models and datasets for mapping and assessment of the RES in urban areas

The second research task was addressed by analysing, assessing, and selecting models and datasets for the ES supply-demand-balance calculation. The available geospatial datasets for the case study, ecosystem types and the Urban Atlas dataset were analysed, updated and integrated into a common database, while preparing a crosswalk between the two datasets. Further adjustments for the Urban Atlas dataset (Chapter 5) were performed with the inclusion and improvement of the details of the green infrastructure classes by integrating the identified UGI classes by Sofiaplan (2020b) (Chapters 4–7). We have used InVEST and EnhancES for the ES assessment.

### 8.1.3. Development of an approach for individual ES supply, demand and balance assessment

Following the literature review, we have identified some of the methods used for ES supply assessment, predominantly using indirect and direct measuring methods, as well as modelling methods, combining remote sensing, earth observation derivatives and, statistical data and field observations. In this regard, we have selected to apply modelling methods for the ES supply assessment (InVEST and EnhanceES) (Chapters 5–7), whereas for the ES demand assessment and the lack of modelling approaches for it, we have combined the existing knowledge on the composite indexes for heat vulnerability (vulnerability and exposure) and updated them with the inclusion of the biophysical component of the ES demand, the hazard indicators (Chapters 6–7). This ES demand assessment approach could be applied to the ES, which has both socio-economic and biophysical components of its demand. The geospatial analyses were performed with the Hot Spot Analysis (Getis-Ord  $G_i^*$ ) and the Optimized Outlier Analysis (Anselin Local Moran's  $I$ ).

### 8.1.4. Development of an integrated approach for urban RES assessment at multiple tiers

The overall integration of the literature review, review of models and data, their applicability assessment and the construction of an approach for supply-demand-balance assessment was implemented in the thesis by applying the integrated multi-tiered approach for regulating ecosystem service assessment in urban areas (Chapter 7). After reviewing and assessing the models and datasets availability for assessment of the six selected priority RES—air purification, noise attenuation, flood regulation, pollination, pest control, and cooling regulation—we have identified that not all services could be assessed at tier 3 (modelling) due to several limitations, including the lack of models for the supply assessment, lack of datasets or uncertainties, etc. The supply of air

purification, flood regulation, and cooling regulation was assessed at tier 3 (modelling), whereas the demand for the three services was also assessed at tier 3 (spatial proxy) with the proposed demand assessment approach (Chapter 7).

We have applied the multi-tiered approach for assessing the remaining three ES—noise attenuation, pollination, and pest control. For each service, we have first assessed the data availability and decided on the respective tier, both for supply and demand assessment. Due to the functional characteristics of pest control, we have decided to apply the expert assessment approach (tier 1), although this tier has the highest uncertainty. For noise attenuation and pollination, we have combined tier 1 and tier 2 for supply and demand assessment. For the supply of noise attenuation, we have applied the expert assessment (tier 1), as no data for assessment at a higher level were selected. For the demand assessment, we have used a dataset from the local noise monitoring at different LULC classes, but due to uncertainties with these datasets, we have applied them as tier 2. For the supply of pollination, we have a spatial proxy with geospatial data of the existing beehives and the foraging distance of bees in the case study, but as those indicators have uncertainties related to the dataset, this approach is situated as tier 2 (Nedkov et al. 2022; Walther et al. 2025). The pollination demand was assessed on tier 1 (expert assessment).

## 8.2. Limitations and uncertainties of methods

The uncertainties of this thesis are associated with data availability, data quality, modelling processes, geospatial database and the expert assessment. We have identified model uncertainty, which consists of uncertainty in the process representation and how the model is performed. Ecosystem service-based models, similar to all models, are simplified representations of reality, which might lead to simplification of some datasets and processes (Wübbelmann et al. 2022). Model uncertainties are related to the input data for the

models. Although the information was predominantly derived from official organisations (municipal enterprises, executive agencies, etc.), we have identified some gaps in the datasets (lack of enough coverage of PM<sub>10</sub> data; lack of rainfall coverage, etc.). Further steps were performed to reduce the uncertainty, such as implementing citizen science data.

### 8.3. Future research directions

Future improvements of the proposed ES assessment approach include applying different scenarios for land use change, especially implementing nature-based solutions (Chen et al. 2025) in the vulnerable areas with a low negative ES balance; integrating another ES-based model; further investigation of the “green wedges” (Stoycheva 2017); further studying ecosystem disservices, etc.

### 8.4. Contributions

We have identified the following contributions of this thesis:

1. Based on a comprehensive literature review, the priority regulating ecosystem services in urban landscapes were identified. The methods used for their assessment, together with the specific features of their application, were systematically analyzed.
2. Spatially explicit approaches were developed for assessing the supply and demand of three priority regulating ecosystem services. The supply assessment is based on the application of specialised models (InVEST and EnhancES), which were adapted and further developed for application in Bulgaria. The demand assessment approach was developed based on existing ecosystem service demand assessment frameworks, incorporating composite risk (vulnerability and exposure) and hazard indices.
3. An approach for the integrated assessment of ecosystem services in urban ecosystems was developed based on the

MAES (Mapping and Assessment of Ecosystems and their Services) methodological framework, using a tiered approach. The applicability of the proposed approach was demonstrated through the assessment of six priority regulating ecosystem services in the city of Sofia.

4. An approach for identifying trade-offs and synergies among ecosystem services was proposed using GIS-based Hot Spot and Outlier analyses.
5. A geospatial database for the urban ecosystems of the Sofia case study area was developed by integrating multiple data sources. Its development was based on a crosswalk system linking different land classification typologies, including national ecosystem types, Urban Atlas classes, and CORINE Land Cover.

Contributions 1–3 have predominantly scientific aspects, whereas contributions 4 and 5 have methodological and applied characteristics.

## 8.5. Conclusions

Although the topic of ecosystem service research has been studied for more than 20 years in Bulgaria, the regulating ecosystem services in urban areas are still not broadly presented. Based on this concept, this thesis contributed to the field of regulating ecosystem services in urban areas by adapting the multi-tiered approach for ecosystem service assessment. Through the literature review results and local needs, we have selected the key regulating ecosystem services to be pilot assessed with the developed multi-tiered approach. The other key results from the review outlined the most applied methods and approaches for urban RES assessment, based on which we have applied one of the most distributed in research ES-based models.

The thesis addresses a knowledge gap identified through the literature review on very few studies assessing ES demand, or both ES supply and demand. This gap has been conceptualised as

integrating biophysical and socio-economic components of the ES demand. This is applied through the socio-economic components via the composite index of vulnerability and exposure. The vulnerability of the population has been expanded with several indicators, addressing the groups of people who have been highly vulnerable to the extreme changes in the ES provision, as well as their geospatial distribution. The biophysical component of the ES demand is the hazard index, which is specific to each of the assessed ES (Chapter 6).

Specific results from the ES assessment show that each LULC class could have a different role in providing or benefiting ES, especially under extreme conditions (Chapters 6–7). Implementing the available dataset was based on classifying them on the three levels of applicability and reliability (tiered approach), based on which we assessed all priority regulating ecosystem services in one dimension, reducing the uncertainties.

## List of Publications

- Stoycheva V, Geneletti D (2023) A review of regulating ecosystem services in the context of urban planning. *Journal of the Bulgarian Geographical Society* 48: 27-42. <https://doi.org/10.3897/jbgs.e93499>
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- Stoycheva V, Nedkov S (2024) The performance of two urban flood regulation models using different input data. *One Ecosystem* 9: e134022. <https://doi.org/10.3897/oneeco.9.e134022>
- Stoycheva V, Nedkov S (2026) Cooling regulation and PM<sub>10</sub> filtration: An approach for integrated supply-demand-balance assessment. *Urban Climate* (Under review).

Stoycheva V, Nedkov S (2026) A multi-tiered approach for integrated assessment of regulating ecosystem services: A case study of Sofia, Bulgaria. *Acta geographica Slovenica* (Submitted).

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