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Sustainable Urban Land Use Optimization Based on Spatial Data

New Scientific Results

of

Ph.D. Dissertation

by

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1. Introduction

Land use optimization is an important tool to achieve sustainable urban land use planning, which aims to achieve long-term balanced urban development through economic prosperity, efficient resources use, environmental protection, and social equity [1]. It is entrusted with allocating different land uses (e.g., residential land, industrial, commercial, recreational facility, open space, etc.) in such a way as to derive optimal benefits [2]. But, in reality, these objectives are competing and even, sometimes, conflicting [3]. For example, if residential development occurs in a low-lying area, it may fulfil the demand for urban housing, but it will create a problem for urban drainage. Construction of building structures may increase economic benefit, but it will deteriorate the environment and urban health. So, careful land allocation is of paramount importance in land use planning. Here comes the concept of land use optimization that allows generating alternative land use scenario from which the decision-maker choose the best option considering conflicting interest [1], [4]. Land use optimization is a branch of spatial optimization that consists of three essential elements. These are a) decision variables, b) objective functions, and c) constraints [5]. A multi-objective land use optimization problem can be formulated as follows [6]:

$$\begin{aligned}
&Minimize\ or\ Maximize && f_m(x), && m = 1,2, \dots\dots....M; \\
&\text{Subject to} && g_j(x) \geq 0, && j = 1,2 \dots\dots\dots\dots.J; \\
& && h_k(x) = 0, && k = 1,2, \dots\dots..\dots K; \\
& && x_i^{(L)} \leq x_i \leq x_i^{(U)}, && i = 1,2 \dots\dots\dots\dots.n;
\end{aligned}$$

Where $f_m(x)$ constitute the objective functions; $g_j(x)$ and $h_k(x)$ are the inequality and equality constraints, respectively. x_i is the spatial decision variable; $x_i^{(L)}$ and $x_i^{(U)}$ are the lower and upper bounds of the decision variable.

The overall aim of this research is to optimize urban land use allocation using spatial data. To achieve this goal, firstly, I have investigated multi-objective urban land use optimization problems through a systematic literature review. By conducting a systematic literature review, I have identified several research gaps on the topic concerned. Then, I have fulfilled some of the research gaps in my study.

2. Objectives

The main objectives of this dissertation are as follows.

a) To investigate multi-objective urban land use optimization problem.
b) To analyse the impact of land use land cover change on urban ecosystem service value.
c) To develop an index to measure social benefits in urban land use optimization problem.
d) To develop an index to measure environmental benefits in urban land use allocation.
e) To present a GIS-based multi-criteria decision-making (GIS-MCDM) approach to optimize sustainable urban land use allocation.

3. Methodology

3.1 Methodology related to objective 1

I have systematically reviewed the urban land use optimization problem using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol [7]. The first step of the PRISMA protocol (Figure 1) is to find research articles. Web of Science Core Collection database and Scopus database was used to find the articles. The second step of the PRISMA protocol is to define eligibility criteria for inclusion and exclusion of articles. Two categories of eligibility criteria are recommended for the inclusion and exclusion of research articles. These are study characteristics (e.g., problem, intervention and study design, etc.) and report characteristics (e.g., geographical location, years considered, language, publication status, etc.) [7]. Following this guideline, I have included those studies which a) explicitly focused on multi-objective land use optimization, b) followed the mathematical approach of optimization, and c) used spatial data. In the case of report characteristics, I have considered the studies which a) focused only on urban areas, b) were written in the English language, c) were published in a peer-reviewed journal article.

In the first stage, based on the search strategy, a total of 2291 articles were initially selected from Web of Science, Scopus, and other sources. In the second stage, I sorted all the articles in MS Excel and removed the duplicate records. Some 865 articles were removed, leaving 1246 articles for the next stage of screening. In the third stage, I have excluded considering exclusion criteria. Thus, 1131 articles are excluded keeping 295 articles for full-text evaluation. In the fourth and final stage, I have scanned these 295 articles thoroughly and finally included 55 articles for this review based on the inclusion and exclusion criteria. These 55 articles were used to identify different aspects of land use optimization problems including objectives, approach to construct problems, solution methods and use of spatial data and model.

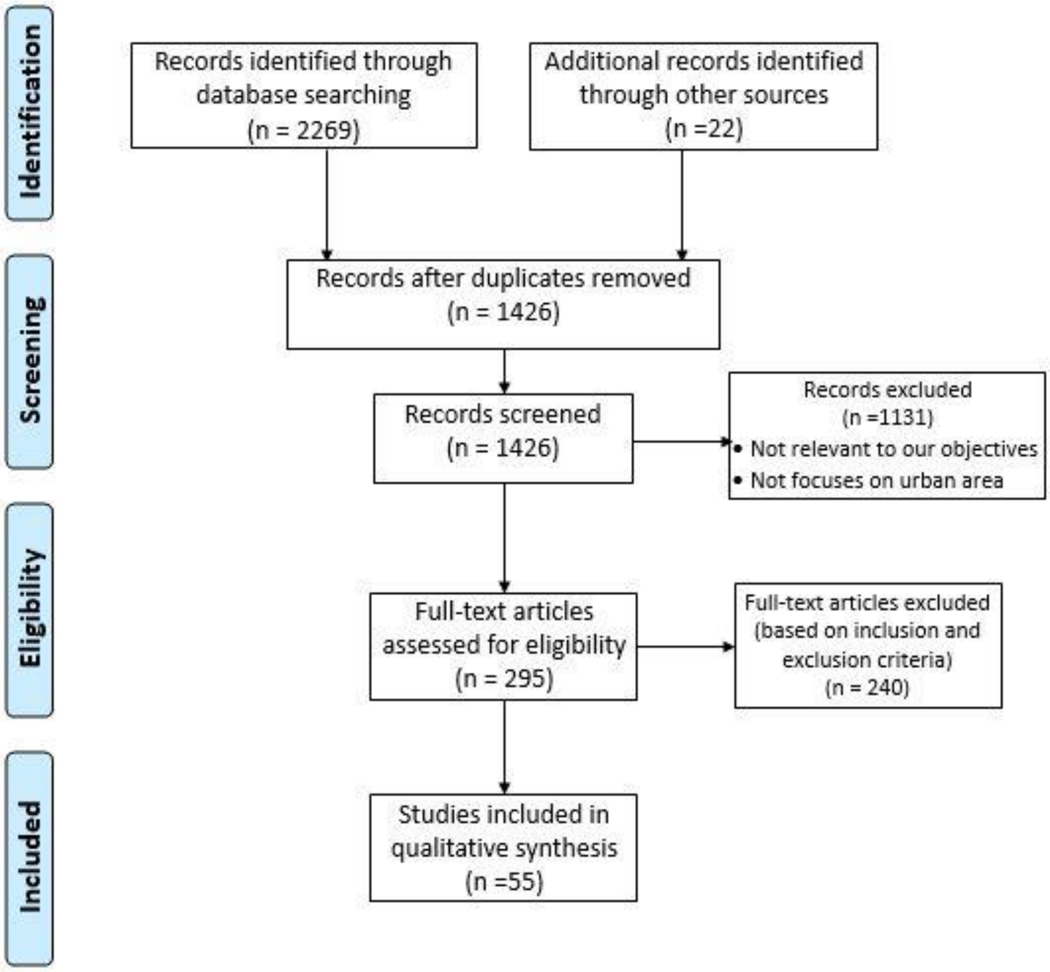

Figure 1: PRISMA flow diagram of the literature search and final inclusion of papers, Adapted from [7]

3.2 Methodology related to objective 2

Ecosystem service value (ESV) has been calculated based on land use and land cover (LULC) of the study area. So, firstly, I have classified the LULC of the study area into five categories namely, a) Agricultural land, b) Waterbody, c) Forest and Vegetation, d) Built-up area, and e) Bare land. I have classified LULC using Landsat images. Then I calculated the ESV based on the five types of LULC. Considering the wider acceptability and applicability, I have used the benefits transfer method (BTM), proposed by Costanza et al. [8], to assess the ESV in the study area. According to BTM, the assessment of ESV comprises three basic steps: a) assignment of LULC to equivalent biome, b) calculation of ESV and its change, and c) elasticity of ESV due to change of LULC. In addition to these steps, I have also conducted a sensitivity analysis to test the robustness and reliability of the ESV assessment. The basic steps are illustrated using Figure 2.

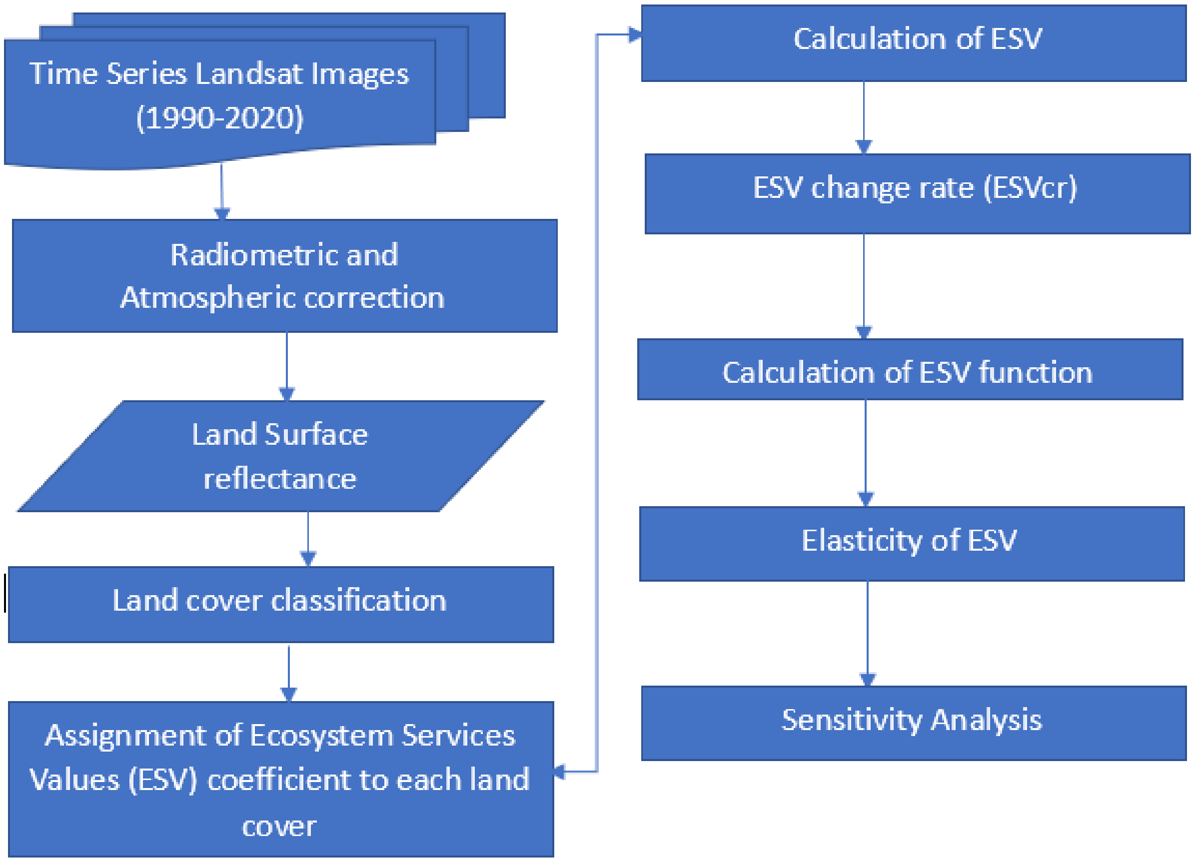

Figure 2: Methodological flow chart of ESV assessment

3.3 Methodology related to objective 3

In order to develop a composite index of social benefit, it necessary to select the appropriate indicators that reflect social benefits from land use allocation. Four indicators namely a) spatial compactness (SC), b) land use compatibility (LC), c) land use mix (LM), and d) evenness of population distribution (EPD) was selected based on literature review and expert opinion. Then, I have calculated the values of all four indicators and standardized the values. Then, by using weighted linear combination (WLC) aggregation function, I have aggregated the indicators and developed the social benefit index (SBI). Analytic hierarchy process was used to determine the weights of the indicators. The basic steps of the methodology were illustrated in Figure 3.

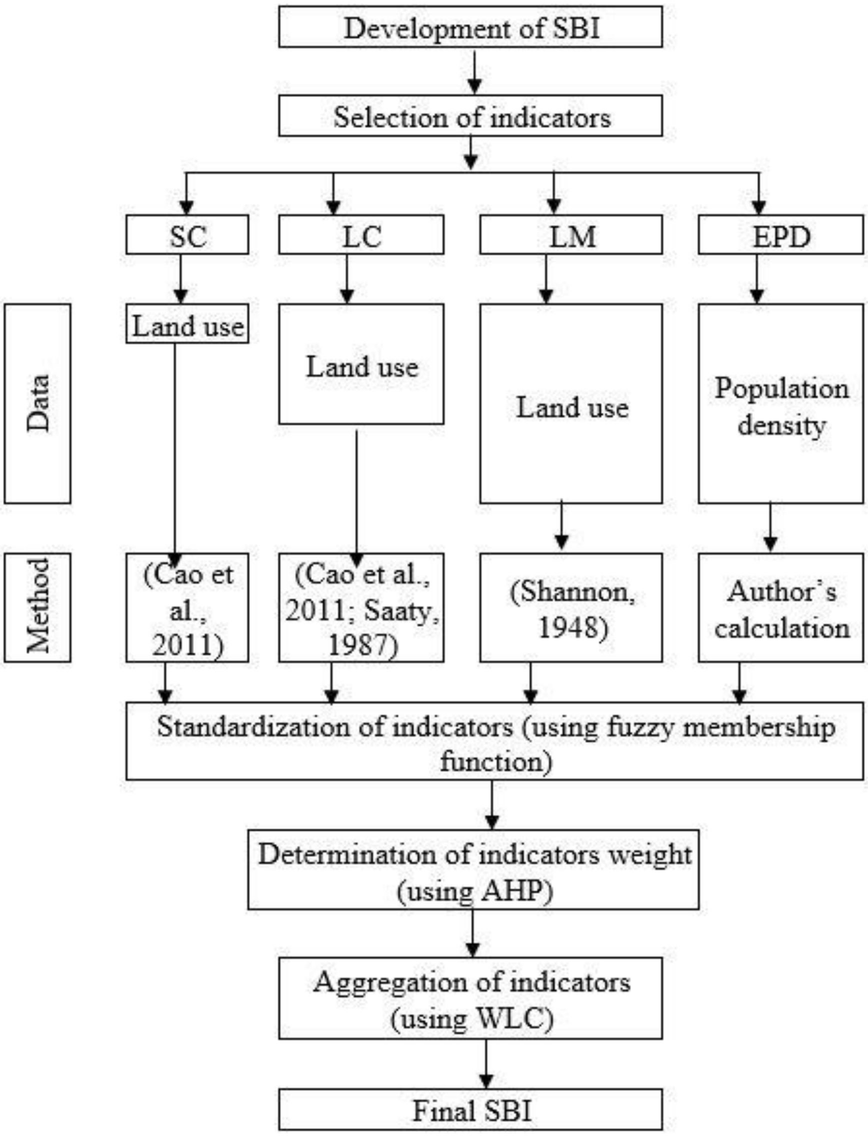

Figure 3: Methodological flow chart of SBI development

3.4 Methodology related to objective 4

To create a composite index of environmental benefit, it is required to use indicators that accurately represent the environmental benefits associated with land use allocation. Four indicators were chosen based on a study of the literature and expert opinion: a) spatial compactness (SC), b) land surface temperature (LST), c) carbon storage (CS), and d) ecosystem service value (ESV). Then, I computed and normalized the results for all four indicators. I then aggregated the indicators and created the environmental benefits index using the ordered weighted averaging (OWA) aggregation algorithm (EBI). The indicators' weights were determined using an analytical hierarchy method. The methodology's fundamental phases are shown in Figure 4.

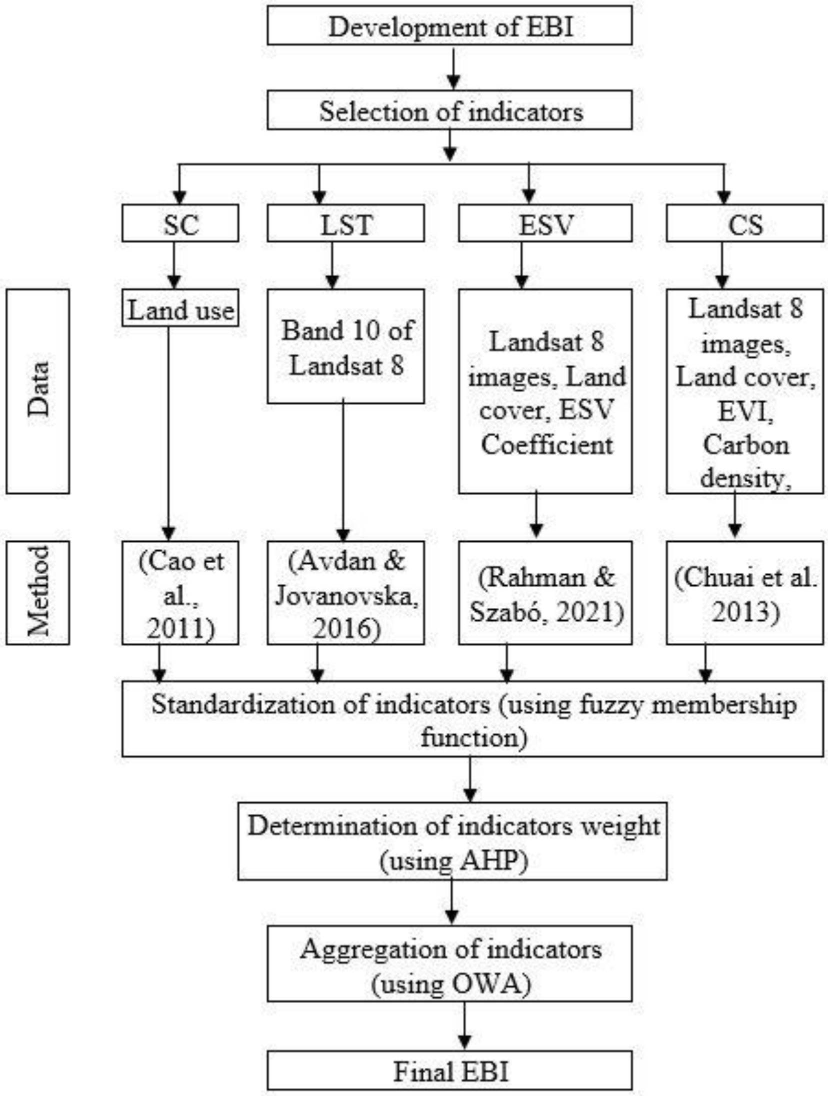

Figure 4: Methodological flow chart of EBI development

3.5 Methodology related to objective 5

For this objective, I have used a variety of datasets. The primary data used in this study include Land use and land cover, road network and other physical features, Digital Elevation Model (DEM). These data were in raster and ESRI shapefile format and were used to derive land suitability maps for different factors. All the data were processed using TerrSet v 19.0 and ArcGIS 10.8 software. I have presented the GIS-based multi-criteria decision making (MCDM) approach to optimize the location for new residential development. I have added sustainability dimensions (social, economic, and environmental benefits) in the process of land use optimization. The whole process of optimizing location for new residential development involves two major steps: a) evaluation of land suitability mapping of residential development using multi-criteria evaluation (MCE) and b) identification of optimal location for new residential development. The four major steps were performed for the evaluation of land suitability. These are a) calculation of criteria value, b) standardization of criteria, c) weighting of criteria, and d) weighted aggregation of criteria. Figure 5 illustrates the methodological steps.

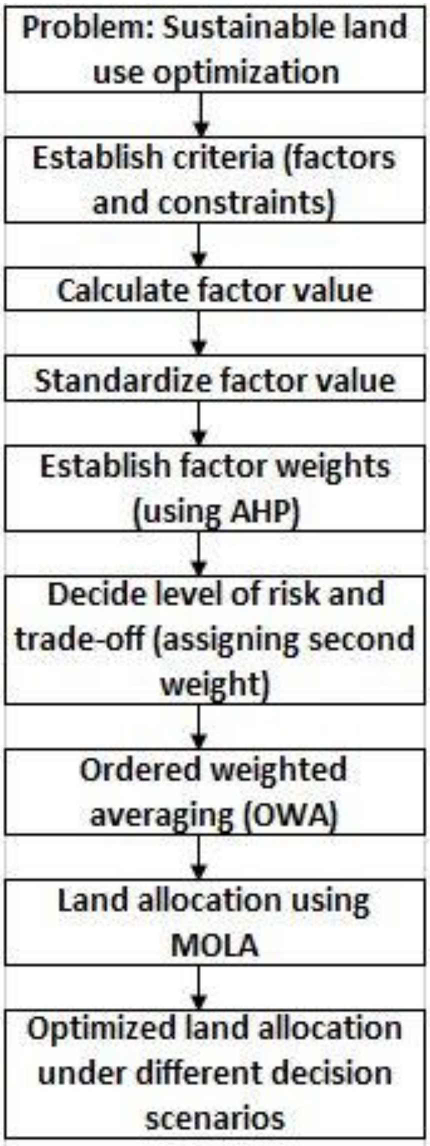

Figure 5: Methodological flow of sustainable urban land use optimization

4. Theses and New scientific results (NSR)

4.1. Thesis 1

I have investigated multi-objective urban land use optimization problems through a systematic literature review. The followings are the new scientific results.

- [NSR 1.1]: The most common objectives in urban land use optimization problems are maximization of spatial compactness (16.67%) followed by maximization of land use compatibility (13.69%), and maximization of land use suitability (11.90%) (Figure 6).

- [NSR 1.2]: Sustainability dimensions (social, economic, and environmental) were poorly addressed in urban land use optimization problems. Only 2 out of 55 studies addressed three dimensions of sustainability.
- [NSR 1.3]: The social dimension of sustainability was not emphasized in urban land use optimization problems. Only 10% (n=3) of studies included social aspects of sustainability.
- [NSR 1.4]: There is no generalized method to calculate social and environmental benefits in urban land use optimization problems. Different researchers used different single variable-based measures of social and environmental benefit. For example, Yuan *et al.* [9] used spatial compactness as a measure of social benefit, and (Gómez-Baggethun et al. [10] used ecosystem service value (ESV) as a measure of environmental benefits.
- [NSR 1.5]: Raster data is the most preferred data model (80%) over vector data (20%) in land use optimization.
- [NSR 1.6]: Participatory approach in land use decision making is very negligible.

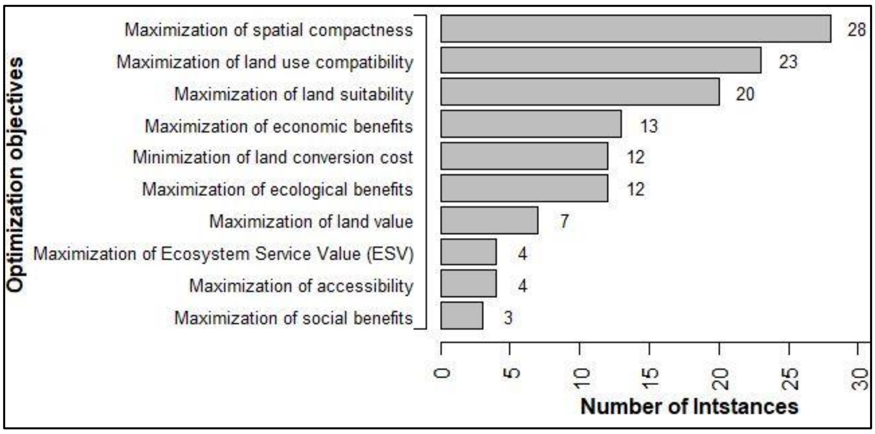

Figure 6: The most frequently used objectives in urban land use optimization problems

4.2. Thesis 2

I have analysed the impact of land use and land cover (LULC) changes on urban ecosystem service value (ESV) of Dhaka city, Bangladesh between the period 1990-2020. The followings are the new scientific results**.**

[NSR 2.1]: Built-up area is the dominating land cover which was increased by 188.35% from 1990 to 2020, with an average annual growth rate is about 6.28% (Figure 7 and Table 1).

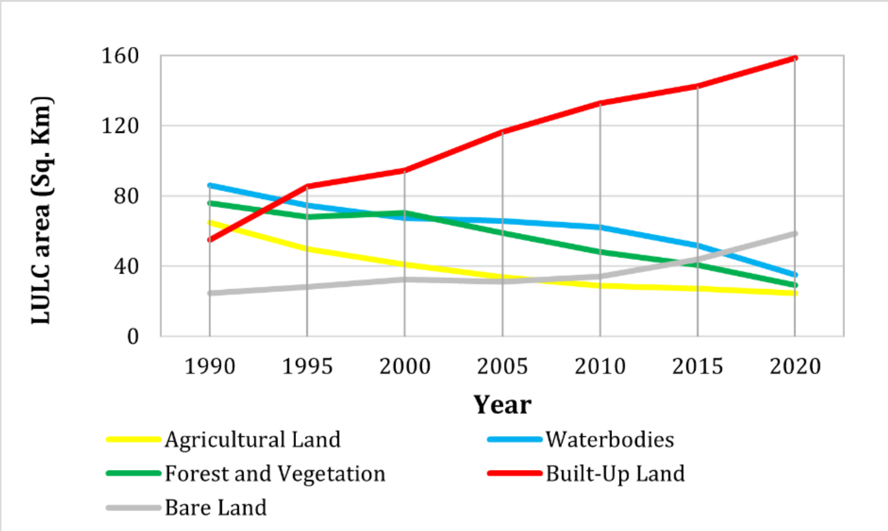

Figure 7. Figure showing trend of LULC change in Dhaka city during 1990-2020.

Table 1. Annual rate of change of LULC during 1990 to 2020.

Land Cover Class	1990-1995	1995-2000	2000-2005	2005-2010	2010-2015	2015-2020	1990-2020
Agricultural Land	-4.66	-3.52	-3.49	-2.88	-1.07	-1.92	-2.06
Water bodies	-2.61	-1.93	-0.54	-1.08	-3.34	-6.49	-1.98
Forest and Vegetation	-2.04	0.68	-3.29	-3.66	-3.10	-5.65	-2.05
Built-Up Land	11.01	2.18	4.64	2.77	1.48	2.26	6.28
Bare Land	2.96	3.12	-0.88	1.94	5.64	6.71	4.61

- [NSR 2.2]: ESV was decreased by 59.55% (85 million USD) from 142.72 million USD in 1990 to 57.72 million USD in 2020 with an average annual decreasing rate is about 1.99% (Figure 8).

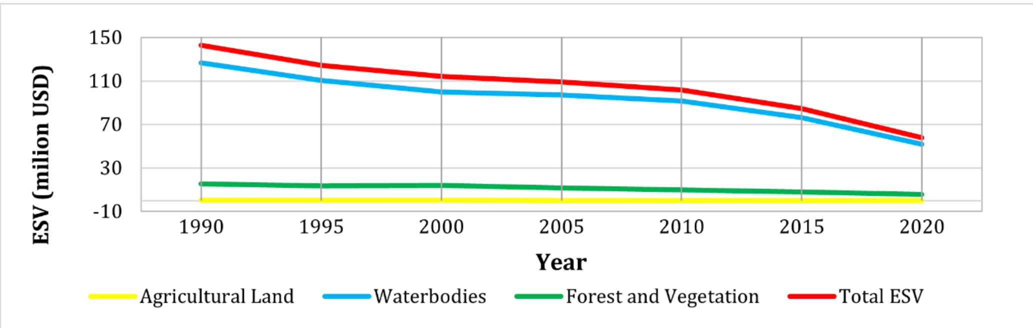

Figure 8. The trend of total ESV in Dhaka city during 1990-2020.

- [NSR 2.3]: The major reason for decreasing ESV was the development of the built-up area through conversion of agricultural land, water bodies, forests, and vegetation land.
- [NSR 2.4]: The water body and regulating service were the highest contributing factors to the total ESV.
- [NSR 2.5]: The result on the elasticity of ESV in relation to LULC implies that about 1% transition in LULC would result in about 0.33% change in total ESV during the study period.

4.3. Thesis 3

I have developed a composite index, the social benefit index (SBI), to measure social benefit in urban land use optimization problems. The followings are the new scientific results.

- [NSR 3.1]: Four variables, namely, spatial compactness, land use compatibility, land use mix, and evenness of population distribution collectively can be used to measure social benefit in urban land use allocation.
- [NSR 3.2]: The industrial and commercial land uses are highly compatible (compatibility =1) whereas residential-industry and industry-health facilities have the lowest compatibility (compatibility = 0.004)
- [NSR 3.3]: The spatial compactness (0.52) is the most influential criterion to the SBI, and the least influential criterion is the evenness of population distribution (0.10) (Table 2).
- [NSR 3.4]: The highest portion of land (40.36%) in the study area falls within the medium SBI zone.
- [NSR 3.5]: SBI is a better approach compared to other single-variable-based measures of social benefit.

Table 2. Weight of different indicators.

Indicators	**weight**
Land use compatibility	0.24
Evenness of population distribution	0.10
Land use mix	0.14
Spatial compactness	0.52

4.4. Thesis 4

I have developed a novel composite index, the environmental benefits index (EBI), to measure environmental benefit in urban land use optimization problems. The followings are the new scientific results.

- [NSR 4.1]: Four variables, namely, spatial compactness, ecosystem service value (ESV), land surface temperature (LST), and carbon storage collectively used to measure environmental benefit in urban land use allocation.
- [NSR 4.2]: The land surface temperature (LST) is the most influential indicator (0.4996) of the EBI, and carbon storage (0.0776) has a low influence on EBI (Table 3).
- [NSR 4.3]: In an average-risk decision, most of the study area (64.55%) falls within the low environmental benefit zone followed by the medium environmental benefit (28.48%) zone.
- [NSR 4.4]: EBI is a better approach compared to other single-variable-based measures of environmental benefit.

Table 3. Weight of different indicators

Indicators	**weight**
Carbon storage	0.0776
Land surface temperature	0.4996
Spatial compactness	0.1667
Ecosystem service value	0.2562

4.5. Thesis 5

I have presented a GIS-based multi-criteria decision-making (GIS-MCDM) approach to optimize urban residential land use allocation. The followings are the new scientific results.

- [NSR 5.1]: Sustainability factors (social, economic, and environmental) were added to traditional factors to optimize urban residential land allocation.
- [NSR 5.2]: Sustainability benefit of residential land allocation was calculated. The result demonstrated that about 9.00% more sustainability benefits can be derived using my proposed approach compared to the traditional approach (Table 4 and Figure 9).
- [NSR 5.3]: Optimum location of residential land was derived under different decision strategies. The “High Risk-No Tradeoff” decision strategy generated the highest sustainability benefit in my case.

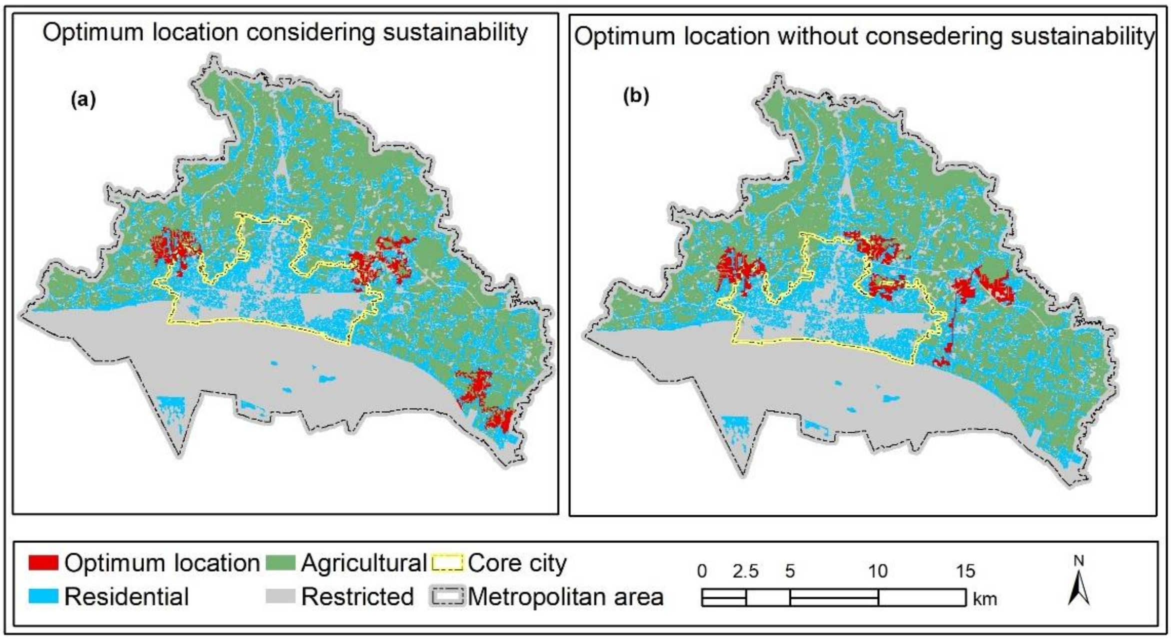

Figure 9: Optimal location of residential land: a) considering sustainability and b) without considering sustainability

Table 4: Sustainability benefits values of optimal land allocation

Sustainability dimension	Sustainability benefit value (unitless)		
	Without considering sustainability	Considering sustainability	% Increase of benefit considering sustainability
Social benefit	95370.08	100775.70	5.67
Environmental benefit	62277.21	67616.00	8.57
Economic benefit	20283.13	25553.56	25.98
Total	177930.42	193945.26	9.00

5. List of all publications connected to theses

Journal papers

1. Rahman, M. M., & Szabó, G. (2021). Multi-objective urban land use optimization using spatial data: A systematic review. Sustainable Cities and Society. 2021, 74, 103214. https://doi.org/10.1016/j.scs.2021.103214
2. Rahman, M.M.; Szabó, G. Impact of land use and land cover changes on urban ecosystem service value in Dhaka, Bangladesh. *Land* **2021**, *10 (8)*, 793. **https://doi.org/10.3390/land10080793**
3. Rahman, M.M.; Szabó, G. A Geospatial Approach to Measure Social Benefits in Urban Land Use Optimization Problem. *Land* **2021**, *10 (12)*, 1398. **https://doi.org/10.3390/land10121398**
4. Rahman, M.M.; Szabó, G. A Novel Composite Index to Measure Environmental Benefits in Urban Land Use Optimization Problem. *ISPRS Int. J. Geo-Inf.* **2022**, *Paper accepted.*
5. Rahman, M.M.; Szabó, G. Sustainable urban land use optimization using GIS-based multi-criteria decision making (GIS-MCDM) approach. *Land.* **2022**, *Paper submitted*

Conference Proceedings

1. Rahman, M. M. and Szabó, G.: NATIONAL SPATIAL DATA INFRASTRUCTURE (NSDI) OF BANGLADESH – DEVELOPMENT, PROGRESS AND WAY FORWARD, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., V-4-2020, 131–138, https://doi.org/10.5194/isprs-annals-V-4-2020-131-2020, 2020.
2. Rahman, M. M., & Szabó, G. (2020). Exploring urban sustainability dimension through land use optimization. In: Molnár, Éva Vanda (ed.) The meeting of theory and practice in GIS XI.: Theory meets practice in GIS. Debrecen, Hungary: Debrecen University Press (2020). ISBN 978-963-318-886-6. pp. 217-222.
3. Rahman, M. M., & Szabó, G. (2021). Comparing K-Means Clustering and Random Forest technique to classify urban land cover. In: Molnár, Éva Vanda (ed.) The meeting of theory and practice in GIS XI.: Theory meets practice in GIS. Debrecen, Hungary: Debrecen University Press (2021). ISBN 978-963-318-977-1. pp. 217-222.

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