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MODELING OF URBAN GRAVITY ZONES AND HIERARCHY OF ADMINISTRATIVE CENTERS IN BOSNIA AND HERZEGOVINA USING THE HUFF MODEL

MODELIRANJE GRADSKIH GRAVITACIJSKIH ZONA I HIJERARHIJA ADMINISTRATIVNIH CENTARA U BOSNI I HERCEGOVINI POMOĆU HUFF MODELA

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ABSTRACT

This research applies the Huff model in delineating urban gravitational zones (UGZs) and hierarchy ranking of administrative centers in Bosnia and Herzegovina. Based on the attributes of travel time (min) and attractiveness, i. e. the mass of the city, gravitational attraction raster models were derived for each center. UGZs were compared with the official administrative units - cantons (FB&H) and regions (RS) based on area and shape attributes. Hierarchy of centers according to UGZs is compared with the official data. Some discrepancies have been observed between theoretical UGZs and actual administrative regions, mostly due to socio-political factors that significantly influence urban development pattern and social dynamics. It was found that polygons of official administrative units are more complex regarding shape than UGZs, indicating a more fragmented structure. The results showed that the average relative difference in area of official administrative units and the UGZs is 60.94%. Out of 16 administrative centers, 10 (62.5%) of them have the same hierarchical rank in both models, while the other six centers differ. An important feature of Huff method is that it uses a spatial model with exact data

SAŽETAK

U ovom radu primijenjen je Huffov model u delineaciji urbanih gravitacijskih zona (UGZ) i hijerarhijskog rangiranja administrativnih centara u Bosni i Hercegovini. Na temelju atributa vremena putovanja (min) i atraktivnosti, odnosno "mase" grada, izvedeni su rasterski modeli gravitacijske privlačnosti. UGZ su uspoređene sa službenim administrativnim jedinicama - kantonima (FBiH) i regijama (RS) na temelju atributa površine i indeksa oblika. Hijerarhija centara dobivenog modela uspoređena je sa službenim podacima. Zabilježena su odstupanja između izvedenih gravitacijskih zona i stvarnih administrativnih regija, uglavnom zbog društveno-političkih čimbenika koji značajno utiču na urbani razvoj i društvenu dinamiku. Utvrđeno je da su poligoni službenih administrativnih jedinica složenijih oblika od UGZ-ova, što ukazuje na fragmentiraniju strukturu. Rezultati pokazuju da je prosječna relativna razlika u površini između službenih administrativnih jedinica i UGZ-ova 60,94%. Od 16 administrativnih centara, njih 10 (62,5%) ima isti hijerarhijski rang u oba modela, dok se šest centara razlikuje. Važan aspekt Huffove metode je korištenje prostornog

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(parameters) and formulas rather than subjective procedures.

Keywords: urban gravitational zones (UGZs), Huff's model, city hierarchy, Bosnia and Herzegovina

modela s točnim podacima (parametri) i formulama umjesto subjektivnih postupaka.

Ključne riječi: urbane gravitacijske zone (UGZ), Huffov model, hijerarhija gradova, Bosna i Hercegovina

1 INTRODUCTION

Cities are product of urbanization developed in response to economic and social needs of surrounding region (Harris and Ullman, 1945). With the accelerated development of cities and its population growth, their functions have changed and expanded significantly (Vresk, 2002). In the past, individual cities were created as a result of exclusively specific functions, e.g. industrial - sources of raw materials (mines, clay deposits, forests) or at the intersections of trade routes. Vresk (1990) defined cities as complex hierarchically organized functional systems, where lower-range settlements, of low functional capacity, gravitate to the city of higher hierarchy level, of high functional capacity (Brown and Holmes, 1971). Hierarchy of the cities is studied within urban geography to better understand urban spaces and interactions between cities (Taylor et al., 2010), and primarily for the optimal planning and development of all levels of settlements connected to central settlement (Magaš, 2013; Bigotte et al., 2014).

The hierarchy of cities is the result of their functions and services (Crkvenčić, 1976; Radeljak Kaufmann, 2015). This concept (Tošić and Nevenić, 2007) is based on the fact that cities, with their multifunctional character, affect regional integration and differentiation of heterogeneous area, forming urban, functional or nodal regions. In such a region, based on the interaction of the city and its surroundings, there is a constant interaction that transforms area through changes in different characteristics (demographic, socioeconomic, functional, physiognomic, etc.). In the 1970s functional urban regional model (Živanović, 2017) appeared from Walther Christaller's Central Place Theory (1933). Here, functional urban area or urban gravitational zone (UGZ) is formed as an area of varying intensity of functional dependence to central settlement (Vresk, 2002; Marić et al., 2024). All settlements by definition, have a certain UGZ which is closely tied to their functions, infrastructure and population. The UGZ delineates areas surrounding a specific city (administrative centers are used in most analyses) where people are drawn to engage in specific activities, that is, to use certain functions of central settlement (Jain and Korzhenevych, 2019; Marić et al., 2024). The population attracted to a particular city determines its 'centrality' or hierarchical rank. A larger population within a city's UGZ signifies higher centrality within a pyramidal hierarchical structure (Seferagić, 2005; Marić et al., 2024). Therefore, defining the UGZ is crucial for informing effective administrative decision-making (Titov, 2021). Although urban hierarchy is closely related to the demographic component, functions and gravitational power of cities (Luo et al., 2023) the physical characteristics of the area, as well as the historical and political context, should not be neglected when defining it. Given the role of cities in territorial development and since they are the basic elements of the settlement network which cannot be studied apart from the surrounding area (Massey et al., 1999) quantification or delineation of their UGZ can serve as a basis for effective administrative-political organization (Huff, 1973; Titov, 2021; Marić et al., 2024). However, a major problem in the delineation of

UGZs is the acquisition of data that reflects the actual intensity of the gravitational attraction phenomenon to the city (Guzik et al, 2017). The UGZs of a city are the result of its functions. However, it was initially considered, in the Reilly's Law of Retail Gravity (1931) (Marić, 2015), that the size of the UGZs mainly depends on the number of the city's population and distance from each other, by modifying Newton's Law of Gravity.

When it comes to the territory of Bosnia and Herzegovina (B&H), the issue of the city's hierarchy and their UGZs remains an open question in professional and academic discourse. It is important to note a significant deficit in scientific studies on this topic. A review of urban and regional geography literature reveals a predominance of research focused on urban development in the post-Dayton context, particularly in the case of Sarajevo (Pobrić and Robinson, 2019; Avdić et al., 2022), where the emphasis is placed on the functions of the city and its physiognomy within the context of post-war restructuring of internal administrative boundaries and integration processes. Gravitational relationships and nodal-functional criteria have been considered from the perspective of potential regionalization of B&H (Osmanković, 2004; Nurković and Mirić, 2005a; Nurković and Miric, 2005b). Geographic studies addressing this topic tend to focus on spatial variations in urbanization within B&H, the size and ranking of settlements (Gekić et al., 2022), the urban planning system (Nurković, 2018), as well as the analysis of the urban system and the hierarchy of cities based on the current territorial organization of B&H (Bıdžan Gekić and Gekić, 2019). It is interesting to note that recent studies also focus on the relationship between urban sprawl and land use (Drašković, 2021). To date, there has been no documented analysis of the gravitational influences and effects of cities based on their functions and demographic components using mathematical-statistical calculations or quantitative methods. Among the reasons for this are the complexity of B&H political-administrative structure, which is considered as one of the most complicated in the world (Woelk, 2023), and the significant role of ethno-political factors in shaping not only the urban hierarchy of cities but also the broader social climate.

In this paper, the Huff model is used to delineate theoretical UGZs based on the population size as a parameter of the city's *attractiveness* or *mass*. Although the Huff 's model has been created to measure the area of influence of retail centers (Huff, 2003), its applicability to various fields and its relative ease of use are reasons for its popularity (Marić, 2015; Moura and Alonso, 2016; Marić and Šiljeg, 2017; Jia et al., 2019; Marić et al., 2024). The primary statistical unit in this study comprises 17 administrative centers of B&H, taking into account the country's current administrative structure. Post-Dayton B&H consist of 143 administrative units, of which 79 are located within the Federation of Bosnia and Herzegovina (FB&H), and 63 within the Republika Srpska (RS). The Brčko District is a separate unit, not under the political jurisdiction of either entity (Ó Tuathail et al, 2006). Selected units include the administrative centers of the cantons, territorial units within the larger entity (FB&H). It includes ten centers: Bihać, Orašje, Tuzla, Zenica, Goražde, Travnik, Mostar, Široki Brijeg, Sarajevo, and Livno. The Republika Srpska is composed of six mesoregions (as defined by the Spatial Plan of RS up to 2025), whose primary regional centers are also included in the analysis: Prijedor, Banja Luka, Doboj, Bijeljina, Istočno Sarajevo, and Trebinje. In addition to these entity administrative centers, the Brčko District is considered as the seventeenth unit in the analysis.

The wartime events, which resulted in a new state structure, including the introduction of an Inter-entity Boundary Line, led to the proliferation of municipalities, as compared to the pre-war administrative organization (Raos, 2010). The current administrative structure pays little attention to the functional aspects of the territory, its physiognomic and nodal differentiation, and its functionality and implications for political and social stability are frequently questioned (Jokay, 2001; Gavrić and Banović, 2013). Given the political and economic challenges B&H faces particularly the processes of political and economic transition, EU integration, and a range of internal challenges (sustainable regional development), it is crucial to examine spatial potentials and dynamics of UGZs.

It is necessary to emphasize that this research is based on the application of the Huff's model, a scientifically and methodologically grounded approach in the delineation of UGZs (Huff, 1973). In the case of B&H, the results of UGZs represent a mathematically derived model of gravitational attraction, which differs from the current administrative-territorial situation. It is well known that in the post-war territorial organization of B&H, the principle of ethnicity played a significant role in administrative reorganization, and such a legacy continues to profoundly influence the current manifestation of gravitational relations (Piacentini, 2019).

2 MATERIALS AND METHODS

Raster models of gravitational attraction or probability of gravitating to a certain administrative center, UGZs and from the resulting hierarchy of the administrative centers of B&H were derived using the Huff model and GIS spatial analysis. The methodological framework can be divided into five steps.

2.1 Network Dataset and „Customers Location"

The first step involved derivation of network dataset and point layer (*costumers*) for which the probability of gravitation to a certain administrative center is calculated. Network dataset is used to calculate the travel distance, or "travel cost" (in minutes) to administrative centers. For this, a *road* layer downloaded from *Geofabrik* website was used. Before the derivation of the network dataset, planarization of road elements was carried out (Šiljeg et al., 2018). It divides overlapping elements into individual and deletes matching lines. This process significantly increases the number of elements and enables a precise calculation of the *travel cost* (min) parameter. Then, for each element, the attribute of distance (km) was calculated and the attribute of the maximum allowed speed for the car was added (OSM, 2024). From derived attributes, the travel time or "cost" (in min) required to traverse a specific element of the road was calculated.

The point layer, representing locations (points) in B&H for which the probability of gravitation to a certain administrative center was calculated, was derived by merging two layers. In the Huff model, this layer is a necessary input dataset and represents *customers*. Since we wanted to create raster models of gravitational attraction to each administrative center the layer of points representing the *costumers* needed to cover the whole of B&H. Therefore, the point layer of B&H populated places was merged with a regular network of points that covers the whole B&H. Therefore, this layer named „*other settlements"* was created by merging layer of populated places of B&H, which includes cities, settlements, villages and hamlets (Geofabrik, 2024) and the layer

of a regular point network created using the *Create Fishnet* tool in ArcMap. The *Cell Size Width* and *Cell Size Height* parameters were set to 4 km, which resulted in a layer of regularly spaced points (n = 3,200 points). Thus, raster models of gravitational attraction to specific administrative centers were derived based on a layer (name=*other settlements*) consisting of over 13,000 elements (Figure 1).

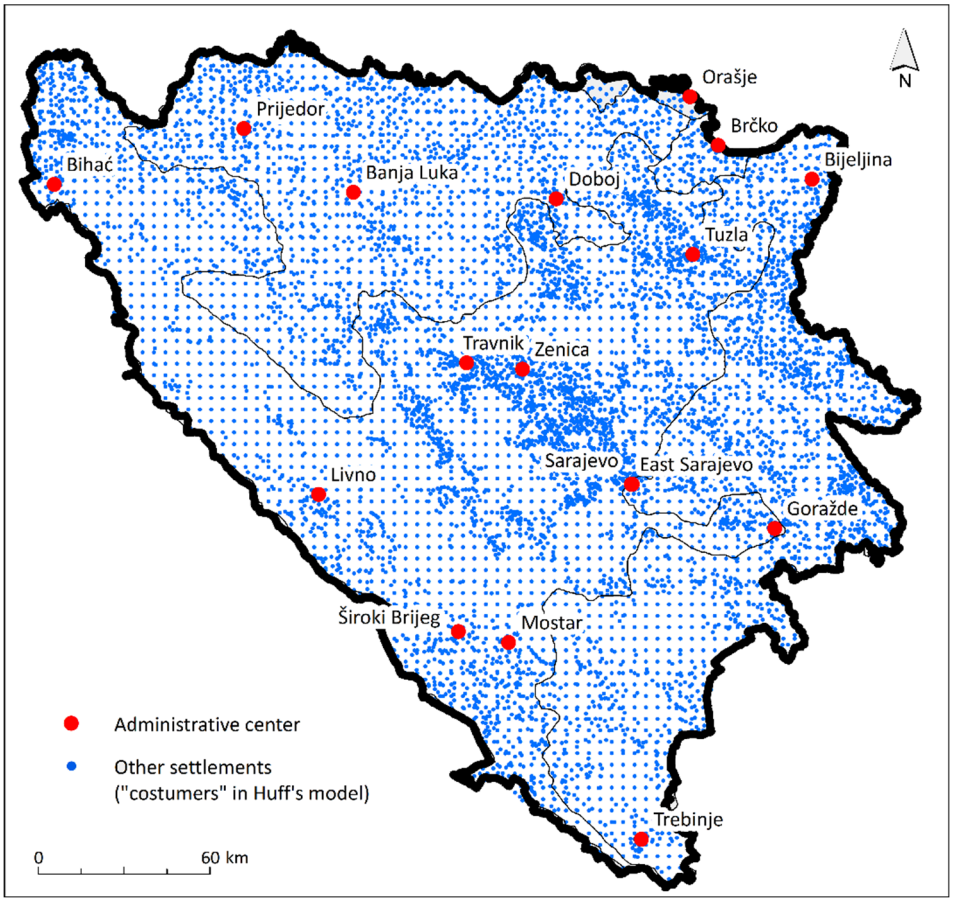

Figure 1. Point layer representing the location of "customers"

2.2 Huff Model Parameters

In the second step, models of gravitational attraction to administrative centers were derived using the Huff's model within the *Market Analysis Toolset* extension in ArcMap (ArcGIS.com, 2024). Huff model was designed in 1963 by David Huff. It is commonly used in a GIS environment for estimating the probability of customers visiting a specific place (eg. market) as a measure of its distance (meters or minutes), attractiveness or size of store and comparative desirability of other places of interest (stores). It can be defined as a probabilistic retail model that calculates gravity-based probabilities (Huff, 1963; Marić and Šiljeg, 2017; Marić et al., 2024). It is based on the assumption that the probability of visiting a certain location is a function of the distance to that

place, its attractiveness, and the distance and attractiveness of competing places from the customer. The formula for the original Huff model is (Huff, 1963):

$$P_{ij} = \frac{\frac{W_i}{D_{ij}^a}}{\sum_{i=1}^{n}\left(\frac{W_i}{D_{ij}^a}\right)}, \quad (1)$$

where:
P_{ij} = is the probability of consumer j shopping at store i,
W_i = a measure of the attractiveness of each store i,
D_{ij} = the distance from consumer j to store i and
a = an exponent applied to distance, distance-decay effect.

The real-time distance parameter (min) to a specific administrative center was derived based on the created network dataset. The attractiveness parameter, i.e. the mass of the city, can be calculated in several ways (Dramowicz, 2005; Marić, 2015; Marić and Šiljeg, 2017; Marić et al., 2024). In the modelling of the gravitational probability to a certain city, data on cities "attractiveness" or "mass" should be calculated as a sum of its functions that "attracts" the surrounding population. The selection and acquisition of the functions and criteria representing its correct functional mass must be done in a way that precisely represents its, in most cases, multiscale functional character (Duhl, 1986; Živković, 2020). This process requires the acquisition of a large amount of diverse data and significant time investment, especially given the challenges of limited availability and inconsistencies in data across all levels of administrative units in B&H. However, the number of inhabitants in a city serves as a reliable indicator of its "attractiveness" or "functional mass". Namely, the number of inhabitants is often a reflection of the functional mass and attractiveness of the city itself, and an indicator of higher centrality in the pyramidal hierarchical structure (Seferagić, 2005). This setting was applied even in Reilly's law of market power, which is a theoretical tool for defining market zones (Liang, 2009). It is based on the assumption that people are attracted to larger places and that travel distance affects the willingness to shop in a particular location (Myles, 2004). The attractive power of a certain object (store, city) is directly proportional to its size (e.g. the number of city residents or the sales area of the store), and inversely proportional to the square of the distance that needs to be overcome from the costumer location to the location of the object (Anderson et al., 2010; Hibbert et al., 2011). This law was traditionally formulated to determine the area of attraction or delineation of market zones between two cities, where the number of inhabitants of a particular city was used as a parameter of attractiveness (Myles, 2004). Therefore, in this analysis, the number of inhabitants of administrative centers was used as a parameter of attractiveness, i.e. the mass of the city. The data on the number of inhabitants were obtained from the official results of the Agency for Statistics of Bosnia and Herzegovina from the most recent census conducted in 2013. The following parameters are set in the *Market Analysis Toolset*:

- *Store Location* is the location of administrative centers (n = 17).
- *Store Name Field* indicates the name of the administrative centers.
- *Store Attractiveness Field* is simulated with the population data of each administrative city.
- *Output Folder* indicates the selected location where the output results are saved.

- *Output Feature Class Name* indicates the name of the layer that represents the output result of the analysis (eg Huff_final).
- *Study Area* means the area within which the analysis was done, and the area of B&H is marked.
- *Use Street-Network Travel Times* option is activated. This made it possible to use the real-time distance parameter expressed in minutes calculated from the network dataset in the analysis.
- *Search Radius Constraints* parameter is set to 200 km. It indicates the maximum distance between administrative centers and the "other settlements" layer for which the probability of gravitation is calculated. For any administrative center further than the search radius, there will be a 0% probability that the location within "other settlement" will patronize these centers. For example, if setting a search radius of 200 km, only centers at a distance of < 200 km from "other settlements" will be considered in determining gravitational probabilities. For any center more than 200 km, there will be a 0% probability that the "other settlements" will patronize these administrative centers.
- *Distance Friction Coefficient* represents a distance-decay effect, i.e. the strength coefficient that determines the strength of the inverse relationship between the probability that the customer (in this case: point in layer "other settlements") will choose a particular store or city and the travel time (min) that the customer must overcome to reach that store or city. A higher coefficient means that the customer is willing to travel less to visit the store or city. Within the *Market Analysis Toolset*, values from 1 to 3 are mostly used, while in this case the coefficient is set to the default value of 2.
- *Origin Locations* represents the point layer ("other settlements") of the location of "customers" in the original Huff model. This layer includes points in B&H for which the probability of gravitation to a certain administrative center is calculated. The process of performing this layer is described in the chapter above.

Therefore, the output result of the *Market Analysis Toolset* is layer "other settlements", in which the attribute of the probability of gravitating to an administrative center that is < 200 km away is calculated for each element. So, if there are five administrative centers from a specific point at a distance of up to 200 km from it, five attributes of the probability of its gravitation are calculated for that element (point).

2.3 Gravitational Attraction Models and UGZs

In the third step, raster models of gravitational attraction and UGZs were derived for each administrative center. Raster models were derived using the inverse distance weighting (IDW) interpolation method. It assigns appropriate weighting coefficients to the points depending on their distance (Medved et al., 2010). The raster models were created using the IDW (3D analyst) tool. The following parameters were set in the IDW tool:

- *Input point feature* represents layer "other settlements" with calculated attributes of gravitational attraction.

- *Z value field* represents the parameter of gravitational attraction to a specific adminstrative center. Depending on which center (e.g. Sarajevo) the raster model was created, the selected attribute was set (e.g. Sarajevo_gravitation_probability).
- *Output raster* sets the location where the raster model is saved.
- *Output cell size* is set at 200 m.
- *Power* is a parameter that controls the dependence of the weighting coefficient on the distance. A value of 2 was left because then it creates the most reliable display of the interpolated values and slightly smoothes the surface.
- *Number of points* specifying the number of nearest input sample points to be used to perform interpolation. A value of 6 points is set.

The UGZs of the administrative centers are derived based on the attribute of gravitational probability in the "other settlements" layer. UGZs represented as polygons that show the area where a specific administrative center has the highest value of attraction, that is, gravitational dominance. For each point (element) within the "other settlements" layer it is determined to which center it gravitates, i.e. for which center it has the highest gravitational probability (e.g. Sarajevo). Then, after selecting those points that have the biggest gravitational attraction towards, for example, Sarajevo, this set of points is „enveloped“ (vectorized) with a polygon layer which represents the UGZ of Sarajevo. While vectorizing the gravity zones, the *Trace Tool* option in the *Editor* was used to avoid the problem of generating topological errors, i.e. overlapping polygons and creating gaps.

2.4 Comparison of Official Administrative Units and UGZs

In the fourth step, the derived UGZs were compared with the official cantons (FB&H) and regions (RS) based on area (km²) and shape (MSI and MFRACT) attributes. For administrative centers in the FB&H, the following cantons were used as official administrative units: Una-Sana (Bihać), Posavina (Orašje), Tuzla (Tuzla), Zenica-Doboj (Zenica), Bosnian-Podrinje (Goražde), Central Bosnia (Travnik), Herzegovina-Neretva (Mostar), West Herzegovina (Široki Brijeg), Sarajevo (Sarajevo) and Canton 10 (Livno). For administrative centers in the RS, the following mesoregions were used as official administrative units: Prijedor mesoregion (Prijedor), Banja Luka mesoregion (Banja Luka), Doboj mesoregion (Doboj), Bijeljina mesoregion (Bijeljina), East Sarajevo mesoregion (E. Sarajevo) and Trebinje mesoregion (Trebinje). Regional structure of Republic of Srpska was acquired from the *Spatial Plan of the Republic of Srpska until 2025*.

The shapes of the derived UGZs and official administrative units (cantons and regions) were quantified using the GIS extension *Vector-based Landscape Analysis Tools (Extension for ArcGIS 10.8): V-LATE 2.0*. It provides a set of the metrics to cover basic ecological and structure-related investigations. For shape quantification, the Mean Shape Index (*MSI*) and Mean Fractal Dimension (*MFRACT*) were used. *MSI* is metric mostly used in landscape analysis to quantify the shape complexity of patches or polygons. It provides a numerical measure of how compact or irregular the patches or polygons are. *SI* for individual element is calculated using following formula:

$$SI = \frac{(P^2)}{4\pi A}, \tag{2}$$

where P is the perimeter of the patch and A is its area.

Values of $SI = 1$ represent perfect circle (most compact shape), $SI > 1$ irregular shapes (less compact, more elongated), and $SI < 1$ very irregular shapes.

Once the Shape Index for each patch, or in this case gravity zone/administrative region, in the, *MS*I is computed as the average of these *SI* values. A lower *MSI* value indicates that most elements/polygons in the landscape are relatively compact in shape, resembling circles or more regular polygons. A higher *MSI* value suggests that patches are more irregular or elongated in shape, indicating a more fragmented or heterogeneous landscape.

The Mean Fractal Dimension (*MFRACT*) is a metric mostly used in landscape analysis to quantify the complexity and irregularity of the patches in landscape. It is derived from the concept of fractal geometry, which describes how patterns repeat at different scales and how complex a shape is, based on its boundary characteristics. The fractal dimension (D) is calculated using the formula:

$$D = 2\frac{\log\left(\frac{P}{A}\right)}{\log(A)}, \tag{3}$$

where P is the perimeter of the patch/element, A is the area of the patch/element and the factor 2 normalizes the perimeter for a standard unit.

The fractal dimension ranges from 1 to 2. When D is closer to 1 the patch is a simple line or has a very simple shape. When patch is closer to 2 it approaches a very irregular, highly convoluted shape, similar to a space-filling curve.

In the modelling of gravitational attraction and UGZs, it is necessary to point out certain characteristics of Huff model. In this case, the below-defined characteristic can be depicted as a shortcoming because of the specific administrative division of B&H. Therefore, because of this deficiency, it was necessary to make a modification in the interpretation of the results acquired by Huff. Mentioned deficiency refers to a situation while modelling gravitational attraction when (1) two administratively separated cities are very close to each other (few km) and (2) they differ significantly in terms of "functional mass" or number of inhabitants. This is the case of administration units or cities of Sarajevo and East Sarajevo, which are located in the FB&H and RS, that is, in the Sarajevo Canton and the Region of East Sarajevo. According to the official census results, Sarajevo has a population of 275,524, whereas the city of East Sarajevo has 61,516 inhabitants - nearly 4.5 times fewer (Agency for Statistics of Bosnia and Herzegovina, 2014). The city of East Sarajevo is more of an administrative rather than an urban-geographical term, encompassing six municipalities of predominantly mountainous character. Within this area, four mini-urban zones are distinctly separated: Lukavica, Pale, Sokolac, and Trnovo (Avdić et al, 2022). Given that it is not a spatially compact gravitational node but rather a collection of settlements on the eastern and southern periphery of Sarajevo, which are in close proximity to each other, the city of East Sarajevo could not be considered as a separate gravitational node for the purposes of generating the model. Therefore, the integration of these two factors (1) Sarajevo's dominance in terms of the 'mass' attribute (population size) and (2) the relatively short distance between them, leads to Sarajevo's predominance over East Sarajevo in the Huff model. Therefore,

due to the mentioned feature of Huff model, which suggests that the population functionally gravitates taking into account the real-time distance and functional mass of the cities, not being limited by state-specific administrative restrictions, the analysis of the gravitational attraction and UGZs of Sarajevo and East Sarajevo is viewed as one raster model and as one gravity zone. This does not in any way question the existing administrative-territorial structure of B&H in the context of the cantons of the FB&H and the regions of the RS, but aims solely to address issues arising from the implementation of the Huff model.

Similar cases in the context of proximity (a few kilometers of distance) of cities and number of inhabitants (dominance of one city in relation to another), but different in the context of administrative and political situation, can also be observed in the Republic of Croatia. For example, in the case of Zagreb and Sesvete. In this case, even though they are two administratively different cities, which have almost "merged" into one, their proximity and intense interaction indicate that this urban area is treated as a single market, which reflects the actual behavior patterns of the population. In other words, both cities are viewed as one entity with one set of characteristics. In the case of Sarajevo and East Sarajevo situation is different regarding the administrative and political situation, but in the analysis we still have to consider it as one element, precisely because of the specifics of the Huff model.

2.5 Hierarchy Ranking of Administrative Centers

In the fifth step, the hierarchy of the administrative centers was derived based to the number of population within their UGZs. The number of population that gravitate to a certain center was calculated by intersecting the UGZs, described in the fourth step, with the demographic raster model (Population Count) downloaded from the *WorldPop* website. The demographic raster model for 2020 represents the estimated total number of people per pixel. Provided in GeoTIFF format, the dataset has a resolution of approximately 100 m, with units representing the number of people per pixel. *"No Data"* values indicate unsettled areas, based on the Built-Settlement Growth Model (BSGM) by Nieves et al. (2020). Converted into a vector layer, the demographic raster model assigns each point the population value (grid value) from an individual pixel. Then, using the *Intersect* and *Dissolve* tools, the number of population was calculated within a specific UGZs of the administrative center. Ultimately, 16 administrative centers (Sarajevo and East Sarajevo are considered as one center due to the reasons explained in the previous paragraph) were classified into five classes according to the hierarchy (city 1. rank, 2. rank, 3. rand, etc.) using the Jenks (natural breaks) classification method.

3 RESULTS

3.1 Models of Cities Gravitational Attraction

Figures 2 and 3 show the raster models of gravitational attraction to the specific administrative center. The spatial resolution of the model is 200 m. The classification method was set to “defined intervals” with a distance of 0.1 or 10%. Gravitational attraction class of < 10% to specific administrative center is symbolized by using the grey colour.

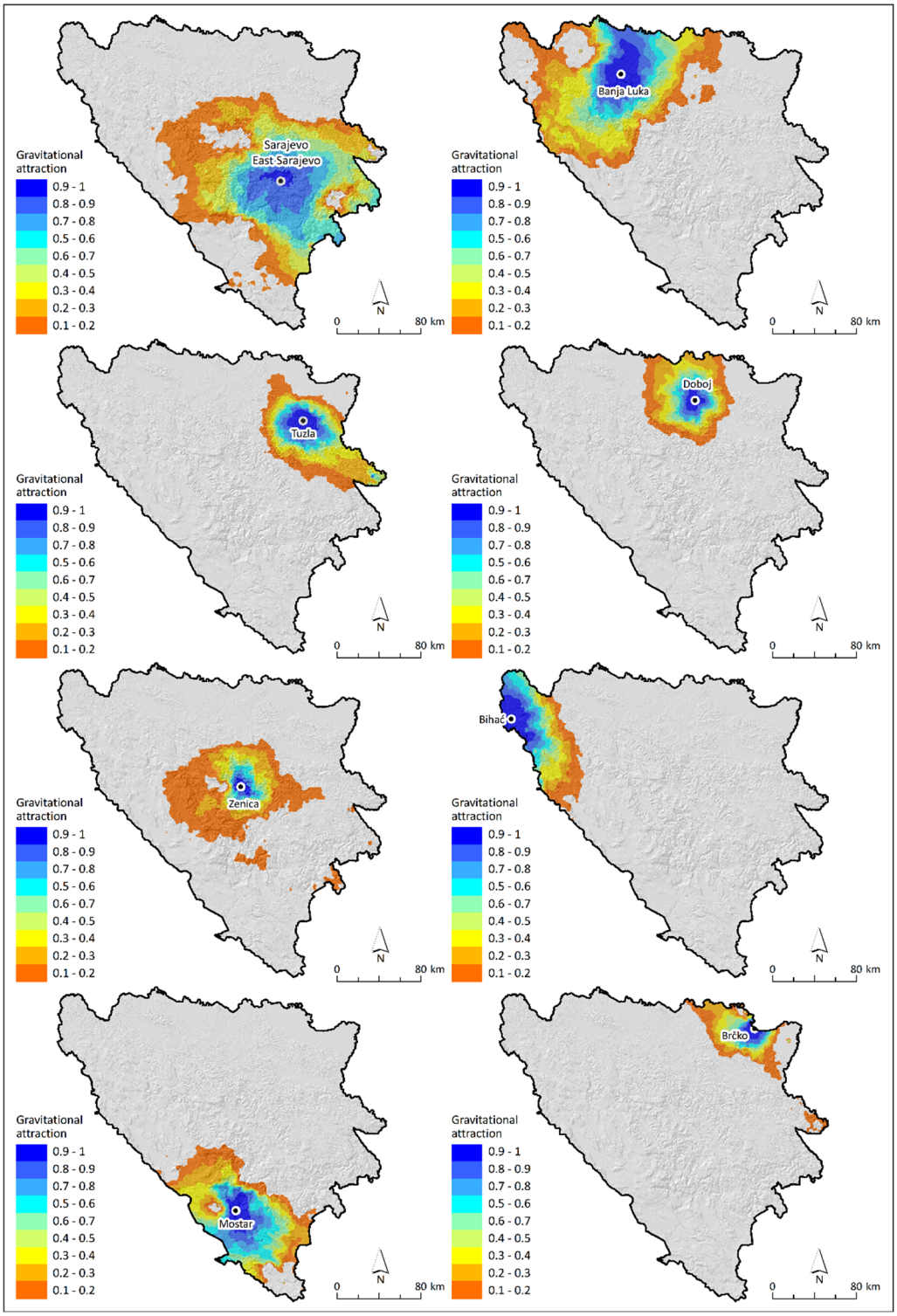

Figure 2. Gravitational Attraction Models for Selected Administrative Center (1)

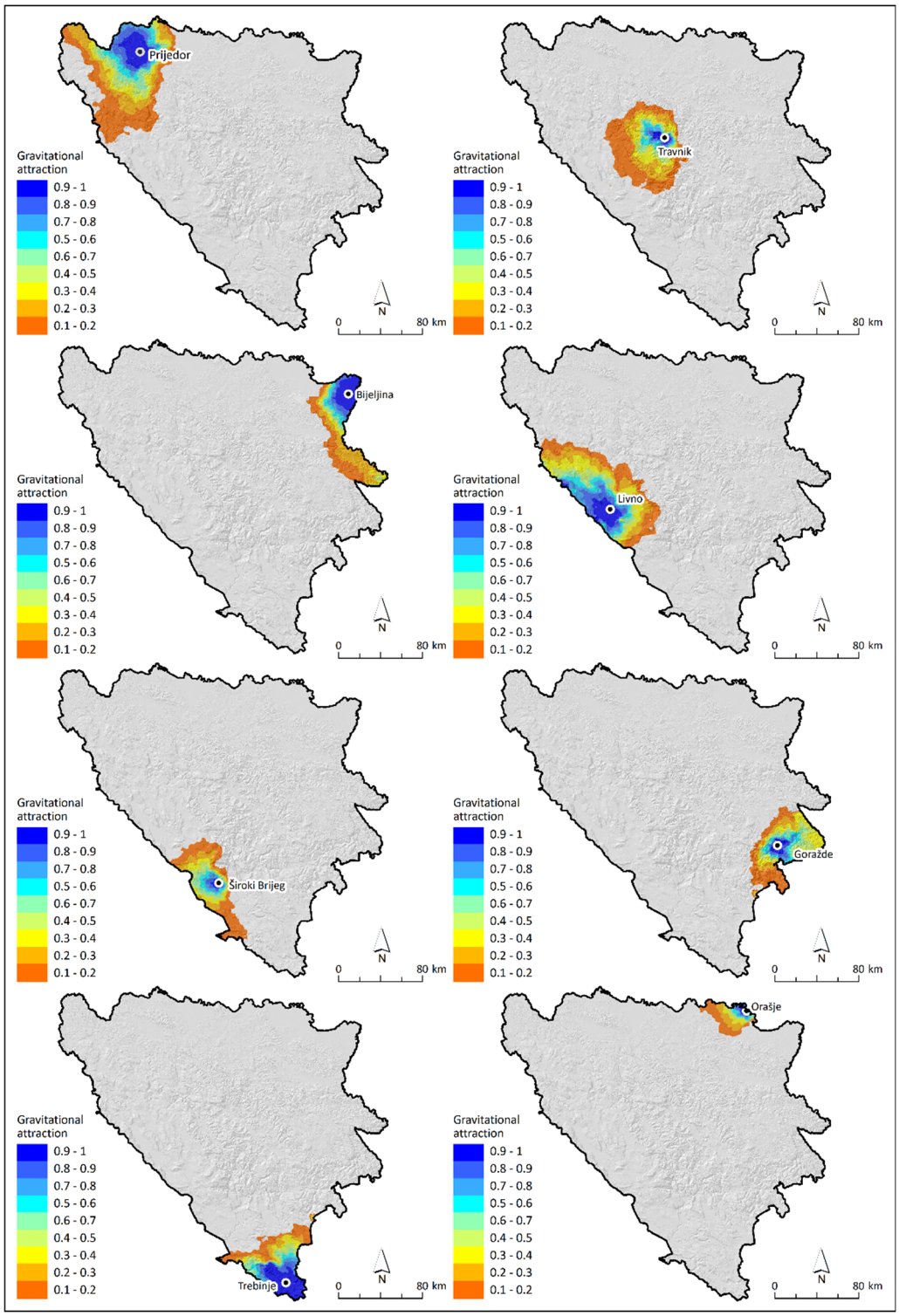

Figure 3. Gravitational Attraction Models for Selected Administrative Centers (2)

3.2 Gravity Zones of Administrative Centers

Figure 4. shows UGZs of administrative centers overlaped with population density raster model acquired from *WorldPop* website. The units are number of people per km². The administrative centers of Sarajevo/East Sarajevo (11,394 km²), Banja Luka (8,583 km²) and Mostar (4,594 km²) have the largest area of the gravity zone. Bijeljina (1,173 km²), Široki Brijeg (1,116 km²), and Orašje (286 km²) exhibit the smallest UGZ areas. The average area of the gravitational zones is 3,252 km². Sarajevo/East Sarajevo, Banja Luka, Mostar, Livno, Tuzla, and Bihać each have gravitational zones exceeding this average, while the remaining centers have areas below 3,252 km².

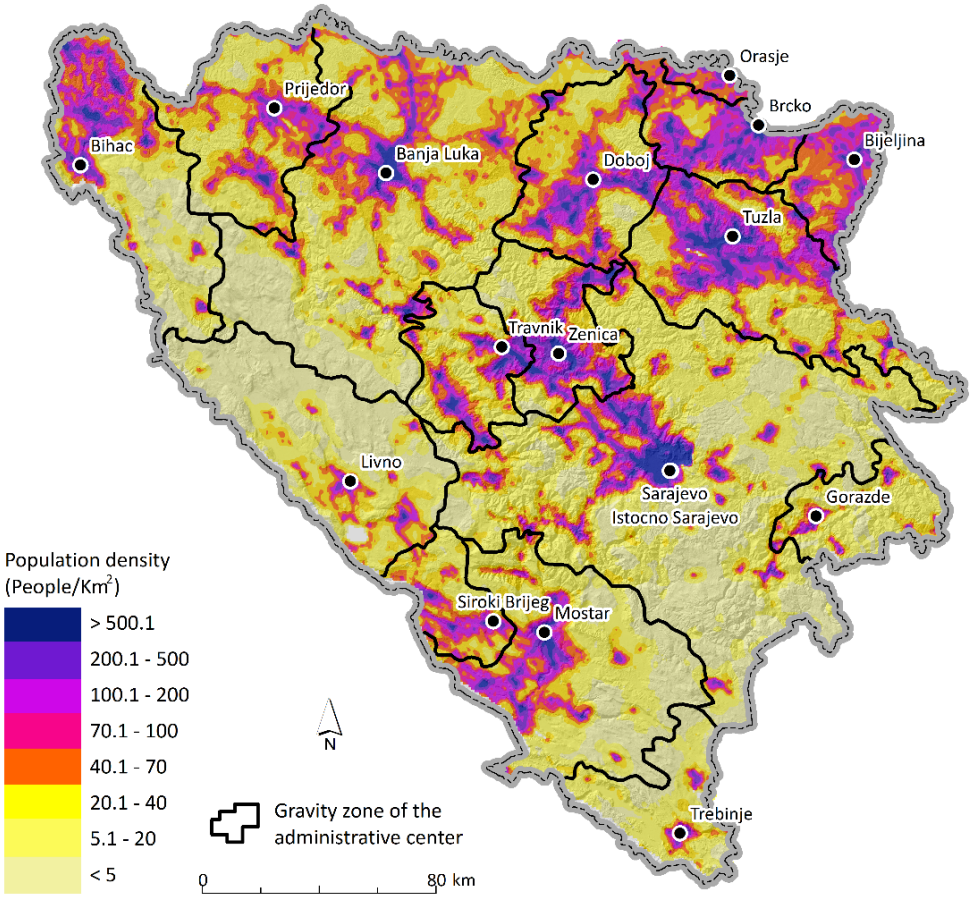

Figure 4. Gravitational Zones of Administrative Centers Overlayed With the Raster Model of Population Density in Bosnia and Herzegovina (2020)
Source: WorldPoP (2020)

3.3 UGZs vs. Official Administrative Boundaries

Table 1 presents a comparison of the area (km²) of cantons in the FB&H and regions in the RS with their corresponding gravitational zones (UGZs). The table displays differences in rank based on the area of official administrative units (Rank_C&R) versus gravitational zones (Rank_GZ), along with calculated absolute (km²) and relative (%) area differences. For instance, the largest difference in ranking is observed for the Trebinje Region, with an official area of 6,011 km², placing it second in Bosnia and Herzegovina by area. According to Huff model, the UGZ of the administrative center of Trebinje encompasses an area of 1,746 km², placing it 10th in terms of size. Thus, Trebinje shows an eight-rank difference between the official area and the UGZ area. Administrative centers with identical rankings for both official area and gravitational zone area include Bihać (6th), Doboj (8th), and Orašje (16th).

Table 1
Comparison of Official Administrative Units and UGZ Based on Area Rank

Cantons and Regions (C&R)			Gravity Zones (GZ)			Rank Diff.	Area Diff.	
Name	Area (km²)	Rank_ C&R	Center	Area (km²)	Rank_ GZ	(C&R)-(GZ)	(C&R)-(GZ)	Rel. (%)
Banja Luka Region	6765.5	1	Banja Luka	8583.3	2	-1	-1817.8	-21.18
Trebinje Region	6011.2	2	Trebinje	1746.2	10	-8	4265.0	244.24
Canton 10	4856.5	3	Livno	4026.5	4	-1	830.1	20.62
Sarajevo Canton/Region E. Sarajevo	4469.4	4	Sarajevo / E. Sarajevo	11394.3	1	3	-6925.0	-60.78
Herzegovina-Neretva	4239.0	5	Mostar	4597.4	3	2	-358.5	-7.80
Una-Sana	4026.4	6	Bihać	3360.8	6	0	665.6	19.81
Zenica-Doboj	3372.5	7	Zenica	1883.3	9	-2	1489.2	79.08
Doboj Region	3260.8	8	Doboj	2582.1	8	0	678.7	26.29
Bijeljina	3224.3	9	Bijeljina	1172.7	14	-5	2051.6	174.94
Central Bosnia	3202.6	10	Travnik	1623.3	11	-1	1579.2	97.29
Tuzla Canton	2635.8	11	Tuzla	3828.5	5	6	-1192.7	-31.15
Prijedor Region	2186.9	12	Prijedor	2831.9	7	5	-645.1	-22.78
West Herzegovina	1225.3	13	Široki Brijeg	1115.8	15	-2	109.5	9.81
Brcko District	512.5	14	Brčko	1467.8	13	1	-955.3	-65.09
Bosnian-Podrinje	490.2	15	Goražde	1531.1	12	3	-1040.9	-67.98
Posavina Canton	361.7	16	Orašje	286.5	16	0	75.2	26.24

The biggest absolute difference in the area (km²) of official administrative units (cantons and regions) and UGZs is recorded for combined Canton Sarajevo and Region of East Sarajevo and their UGZs. The results show that the UGZ of Sarajevo/East Sarajevo is larger by 6,925 km² (about 60%) than the Canton Sarajevo and Region of East Sarajevo. The next largest absolute difference is recorded for Trebinje, whose region has an area of 6,011 km², and a UGZ is only 1,746 km², which gives an absolute difference of 4,265 km², i.e. the Region of Trebinje is 244.24% larger than its derived UGZ. The largest relative differences (%) are found in Trebinje and Bijeljina, with the Bijeljina region having an official area 175% larger than its derived UGZ. Among the 16 administrative centers, nine (Trebinje, Livno, Bihać, Zenica, Doboj, Bijeljina,

Travnik, Široki Brijeg, and Orašje) possess a larger administrative area than their UGZs. In contrast, the remaining seven centers (Banja Luka, Sarajevo/East Sarajevo, Mostar, Tuzla, Prijedor, Brčko, and Goražde) have UGZs that exceed the area of their official administrative units.

The smallest relative differences are observed in Mostar, where the cantonal area is 7.8% smaller than its UGZ, and in Široki Brijeg, where the official area is 9.81% larger than the UGZ. Across all administrative centers, the average relative difference between the areas of official administrative units (cantons and regions) and UGZs is 60.94%. Consequently, the relative correspondence between UGZ areas and official administrative areas (cantons and regions) is 39.06%.

Table 2 presents the shape index (SI) and fractal dimension (FD) calculated for official cantons and regions, as well as for the derived gravitational zones. The average shape index value (MSI) for the cantons and regions is 2.131, while the average value for the gravitational zones is 1.766. Among the 16 administrative centers, 14 (87.5%) exhibit higher shape index values for their official administrative borders compared to the derived gravitational zones. Only the gravitational zones for Goražde and Sarajevo/East Sarajevo have higher shape index values than their respective administrative regions. The greatest similarity between official administrative units and gravitational zones, according to the shape index metric, is observed in Travnik (0.4%) and Banja Luka (4.9%).

Table 2
Comparison of Official Administrative Units and Gravitational Zones Based on Area and Hierarhical Structure

Admin, Region Canton and Region	SI	FD	Admin. Center Gravity_Zones	SI	FD	C&R-GZ		
						SI	FD	Rel. Diff.
Banja Luka Region	2.198	1.181	Banja Luka	2.096	1.175	0.10	0.006	4.9
Una-Sana Canton	2.107	1.181	Bihać	1.758	1.167	0.35	0.014	19.9
Bijeljina Region	2.463	1.198	Bijeljina	1.530	1.162	0.93	0.036	61.0
Brčko District	2.059	1.199	Brčko	1.799	1.176	0.26	0.023	14.5
Doboj Region	2.511	1.200	Doboj	1.410	1.149	1.10	0.051	78.1
Bosnian-Podrinje	1.404	1.160	Goražde	1.767	1.173	-0.36	-0.013	-20.5
Canton 10	1.632	1.157	Livno	1.483	1.150	0.15	0.007	10.0
Herzegovina-Neretva	2.625	1.201	Mostar	1.875	1.170	0.75	0.031	40.0
Posavina Canton	2.619	1.227	Orašje	1.891	1.195	0.73	0.032	38.5
Prijedor Region	2.121	1.188	Prijedor	1.587	1.159	0.53	0.029	33.6
Sarajevo Canton/Region E. Sarajevo	2.127	1.182	Sarajevo/E. Sarajevo	2.371	1.184	-0.24	-0.002	-10.3
West Herzegovina	2.070	1.190	Široki Brijeg	1.426	1.156	0.64	0.034	45.2
Central Bosnia	1.702	1.164	Travnik	1.696	1.169	0.01	-0.005	0.4
Trebinje Region	2.170	1.181	Trebinje	1.792	1.174	0.38	0.007	21.1
Tuzla Canton	2.256	1.192	Tuzla	1.943	1.175	0.31	0.017	16.1
Zenica-Doboj	2.034	1.180	Zenica	1.836	1.175	0.20	0.005	10.8

The average FD value (MFRACT) of cantons and regions is 1.186, while the average value for UGZs is 1.169. Among the 16 administrative centers, 13 (81.25%) exhibit higher fractal dimension (FD) values for their official administrative boundaries compared to the UGZs. Only the UGZs of Goražde, Travnik, and Sarajevo/East Sarajevo have higher FD values than their corresponding official administrative regions. Consequently, with respect to the MSI and mean fractal dimension MFRACT, the administrative units of cantons and regions have higher average values compared to the derived UGZs. This finding suggests that the polygons representing official administrative units are more irregular or elongated in shape than those of the UGZs, indicating a more fragmented or heterogeneous structure.

3.4 Hierarchy Rank of Administrative Centers

Table 3 presents the hierarchy of administrative centers derived from the population residing within their UGZs. The total population figures differ from official data because they are calculated using a demographic raster model (Population Count) obtained from the WorldPop website. The population within the UGZs for the 16 administrative centers is classified into five classes/rankings (1st order city, 2nd order city, 3rd order city, etc.) using Jenks classification methods. The hierarchy of administrative centers would be following (Table 3):

- 1st order (Sarajevo/East Sarajevo, Banja Luka, Tuzla)
- 2nd order (Doboj, Zenica, Bihać, Mostar, Brčko)
- 3rd order (Prijedor, Travnik, Bijeljina)
- 4th order (Livno, Široki Brijeg)
- 5th order (Goražde, Trebinje, Orašje)

Table 3
Hierarchy of Administrative Centers According to Different Classification Methods for Huff Result

PoP. in GZ	Administrative centers	*Jenks method* Rank
649708	Sarajevo and East Sarajevo	1
412091	Banja Luka	1
409843	Tuzla	1
257869	Doboj	2
227659	Zenica	2
211482	Bihać	2
203373	Mostar	2
198819	Brcko	2
160420	Prijedor	3
146003	Travnik	3
131417	Bijeljina	3
70075	Livno	4
66950	Široki Brijeg	4
51135	Goražde	5
37227	Trebinje	5
32425	Orašje	5

Table 4
Hierarchy of Administrative Centers According to Official Population Data in Cantons or Regions

PoP. in Cantons/Regions	Administrative Centers	*Jenks method* Rank
536322	Sarajevo/East Sarajevo	1
445028	Tuzla	1
405225	Banja Luka	1
364433	Zenica	2
276101	Bijeljina	2
273261	Bihać	2
254686	Travnik	2
222007	Mostar	3
208134	Doboj	3
148396	Prijedor	3
94898	Široki Brijeg	4
84127	Livno	4
83516	Brčko	4
67838	Trebinje	4
43453	Orašje	5
23734	Goražde	5

To compare the hierarchy of administrative centers based on the population within their UGZs to the actual state, a hierarchy of cities was established according to the population counts in cantons and regions, which represent the official administrative units (Table 4). The population attribute for these official administrative units was also classified using the Jenks method into five classes or ranks (1st-order city, 2nd-order city, 3rd-order city, etc.). Based on the population in official administrative units the hierarchy of centers would be following (Table 4):

- 1st order (Sarajevo/East Sarajevo, Banja Luka, Tuzla)
- 2nd order (Zenica, Bijeljina, Bihać, Travnik)
- 3rd order (Mostar, Doboj, Prijedor)
- 4th order (Široki Brijeg, Livno, Brčko, Trebinje)
- 5th order (Orašje, Goražde).

4 DISCUSSION

4.1 Validity of Results

The differences between the obtained model and official cantons and regions are most apparent when analyzing the area and shape of the UGZs and official administrative units (Table 1). As illustrated in the Figure 2, the largest UGZ is observed for three centers: Sarajevo/East Sarajevo, Mostar and Banja Luka. Taking into account both the area covered and the population within the defined region, the gravitational zone of Sarajevo/East Sarajevo exhibits the strongest gravitational pull, positioning it as the primary nodal center (highest rank). This is primarily due to its demographic mass, which is indirectly reflected in its diverse functional character. Sarajevo serves as the main administrative, political, cultural, educational, and academic hub of the country

(Nurković, 2016; Gül and Dee, 2015), and due to the multidimensional nature of its functions, it attracts the largest number of inhabitants. The results for Sarajevo/East Sarajevo indicate a significantly larger gravitational zone than the official one - specifically, 60% larger. The example of Sarajevo clearly demonstrates that administrative boundaries often do not align with economic and social ties, thus limiting the flow of people, goods, and services, creating barriers that diminish the gravitational attraction of the city, even when, in practice, it could be greater.

In the case of Trebinje, the reverse situation is observed. The UGZ of Trebinje, as determined by the Huff model, is nearly 2.5 times smaller than the official Trebinje region. This discrepancy in results highlights the necessity of understanding the complex factors which can affect on the determination of official administrative boundaries. Namely, Trebinje is characterized by a peripheral position in relation to the rest of the country and its corresponding entity (Botić, 2015). Its designation as a transportation hub, as indicated by proposed airport construction outlined in the Spatial Plan of the Republic of Srpska 2025, coupled with its status as the most economically dominant center in Eastern Herzegovina, substantially impacts its gravitational performance. Therefore, Trebinje is recognized as a critical development axis of the Republic of Srpska (Trebinje City Development Strategy 2018-2027), to which the more demographically and economically marginalized municipalities in this part of the country (Nevesinje, Gacko, Bileća, and Ljubinje) gravitate (Marić and Avdić, 2023).

The gravitational zones obtained for Mostar and Banja Luka indirectly reflect the significance of these centers in both functional terms and their administrative importance in the national context as macro-regional centers. The UGZs of Livno, Bihać, Zenica, Travnik, Široki Brijeg and Orašje, which function as cantonal centers are smaller in area than their official boundaries. For the remaining centers, primarily Tuzla (along with Mostar and Banja Luka), Huff model indicates a larger UGZs than the official one, suggesting that according to the demographic mass of these cities their actual administrative unit could be bigger. This is also the case for Goražde and Prijedor although its gravitational influence is diminished by their peripheral location within their respective entities.

It is evident that the results derived by Huff model differs from the current situation in B&H. This is because administrative boundaries frequently reflect legal and cultural differentiations that can influence the perception of gravitational attractiveness. In the case of B&H, ethnopolitical factors that shape social reality are deeply embedded in the spatial-social dynamics and conditions. Ethnic homogenization and territorialization in the post-war period have proven to be significant barriers to creating functionally coherent regions (Pejanović, 2018). This is most apparent at the local/municipal level, where the majority of residents prefer to fulfill their social, health, administrative, educational and other existential needs in areas where their ethnic group is the majority, rather than in a closer and mathematically more logical city with a different ethnopolitical climate (Dnevni Avaz, 2016; AlJazzera, 2016; Blijesak.info, 2017).

When comparing the official hierarchy rankings of administrative centers with those derived from Huff model based on population within UGZs, as well as those based on cantons and regions, it is evident that there are minimal differences in the hierarchical rankings (Table 5).

Table 5
Hierarchy Ranking of Administrative Centers According to Official Data and UGZs

Administrative centers	Hierarchy (PoP in UGZ)	Hierarchy (Official Pop)	Difference in rank (Official - UGS)
Sarajevo/East Sarajevo	1	1	0
Banja Luka	1	1	0
Tuzla	1	1	0
Zenica	2	2	0
Bijeljina	3	2	-1
Mostar	2	3	1
Prijedor	3	3	0
Brčko	2	4	2
Doboj	2	3	1
Bihać	2	2	0
Travnik	3	2	-1
Livno	4	4	0
Trebinje	5	4	-1
Široki Brijeg	4	4	0
Goražde	5	5	0
Orašje	5	5	0

Among the 16 administrative centers analyzed, 10 (62.5%) - namely Sarajevo/East Sarajevo, Banja Luka, Tuzla, Zenica, Prijedor, Bihać, Livno, Široki Brijeg, Goražde and Orašje exhibit identical hierarchical rankings in both models. In contrast, the remaining five centers (Bijeljina, Mostar, Brčko, Doboj, Travnik, Trebinje) differ in hierarchy. All mentioned administrative centers, except Brčko, differ by one rank in the hierarchy, while Brčko differs by two positions. The reasons for Brčko's elevated gravitational potential can be attributed to its strategically significant location in the northeastern part of the country. Additionally, its unique administrative and political status may exert a notable gravitational effect (Development Strategy of the Brčko District of Bosnia and Herzegovina, 2021–2027). Brčko's special administrative autonomy enhances its capacity to provide services and attract people from surrounding municipalities. Beyond Bijeljina, there are no other demographically or functionally significant centers in the vicinity, which further increases Brčko's relative attractiveness. Furthermore, its transport connectivity, as a key multimodal transportation hub, amplifies its gravitational pull (Evropski univerzitet Brčko Distrikt, 2022).

As anticipated, the hierarchical positions of the largest (1st) and smallest (16th) centers, based on UGZs and official data, generally align (Marić et al., 2024). For instance, in both models, the top four centers—Sarajevo/East Sarajevo, Banja Luka, Tuzla, and Zenica maintain the same ranking, as do the bottom three centers, Široki Brijeg, Goražde and Orašje (Table 5).

Although according to the population within the UGZ, Banja Luka has a bigger number of population who gravitate to it than Tuzla, according to the official data (number of population in cantons and regions), this is not the case. Nevertheless, after the classification of both attributes, both Banja Luka and Tuzla are classified as centers of the 1st order with Sarajevo/East Sarajevo. The larger population within the UGZ of Banja Luka can be attributed to its status as the principal administrative center of the RS, one of the country's entities. Tuzla, also as the 1st order center

and as the largest city of the region (Kadušić, 2013) attracts a significant number of population primarily due to its strong industrial base, which has influenced the development of the city's educational, healthcare, and administrative functions (Bećirović and Kudumović-Dostović, 2020). A similar situation is observed with Zenica, an industrial center that, due to its proximity to Sarajevo and its favorable geographical position, primarily owing to Corridor Vc (Marić, 2012), is ranked as the 2nd order center (both officially and according to Huff model).

Huff model overestimated Mostar and Dobroj hierarchical position by one rank and Brčko's hierarchical position by two ranks. Mostar, as the center of the Herzegovina-Neretva Canton and the broader Herzegovina region, has a significant gravitational reach, considering its functions and overall urban dominance within the system of urban settlements in Herzegovina, a position further strengthened by its cultural, demographic, and historical components (Đurasović and Knieling, 2015). The importance of Doboj as a significant node, as assessed by the Huff model, exceeds its current administrative rank due to several factors. Similar to Brčko, one key factor is its excellent transportation connectivity. With the post-Dayton administrative reorganization of Bosnia and Herzegovina, new municipalities were formed from parts of the Doboj territory. (Raos, 2010). Furthermore, its gravitational power diminished with the establishment of Zenica as the main administrative center of the Zenica-Doboj Canton

On the contrary, the Huff model underestimated the hierarchical position of Bijeljina, Travnik and Trebinje by one rank. UGZs with fewer than 100,000 inhabitants include administrative centers of cantons and meso-regions such as Livno, Široki Brijeg, Goražde and Trebinje. UGZs with around 50,000 inhabitants include Goražde and Orašje, which, due to generally more negative demographic trends caused by a range of factors, including socio-economic and physical-geographical factors, exhibit lower gravitational pull (5th rank)

4.2 Future Improvements

In the derivation of UGZs, the attributes used included travel time in minutes, while the attractiveness of the centers was represented by the demographic component, constituting the ″mass of the city″. Since the mass of a city is best represented by its functions, future considerations should involve incorporating these parameters (Marić et al., 2024) into Huff models, which would provide a more comprehensive picture of the true mass of a city. This modeling approach, given that it is a possibilistic model, can also be applied to lower administrative levels, such as municipalities (Huff, 1973; Titov, 2021).

The accuracy assessment of the derived hierarchical models and UGZs would be best achieved by supplementing the criteria (such as the functions of the city) and conducting a qualitative analysis (e.g., surveys on gravitational relations), particularly in the case of B&H. The survey research would allow the verification of the model's accuracy and its calibration in the context of determining the parameters of the *distance-decay effect* within Huff model. It is particularly useful for ″transitional zones″ between one gravitational area and another.

This research represents one of the multiple possible approaches in modeling UGZs, which can be enhanced with a comprehensive set of additional criteria. Modeling the accurate gravitational zones of cities plays a crucial role in spatial planning and development, enabling a precise understanding of the dynamics between urban centers and their surrounding areas. This process

aids in identifying the real influences that cities exert on their broader regions, which is essential for making informed decisions regarding spatial development, infrastructure investments, and regional policies. An important feature of this methodological approach is that it utilizes a spatial model with exact formula and data (which can be very comprehensive) rather than subjective or empirical procedures.

In the case of B&H, modeling gravitational zones holds particular significance given the specific political-administrative context of the country, where the gravitational relationships of urban zones are often shaped by ethnic criteria. By modeling gravitational zones based on actual socio-economic and demographic factors, also including historical and cultural ties, it is possible to identify functionally coherent regions that reflect the real flows of people, goods and services. This approach enables more efficient and sustainable development, as spatial planning is grounded in objective indicators of gravitational relationships (Kurowska et al., 2017).

5 CONCLUSION

In this paper, Huff model was used to derive the urban gravitation zone (UGZ) and the hierarchy of selected administrative centers of B&H. Based on the attributes of travel time in minutes and attractiveness, i.e. the mass of the city, gravitational attraction raster models were derived for each center. The UGZ of each city was delineated from the obtained models. UGZs were compared with the official administrative units, cantons (FB&H) and regions (RS), based on area and shape attributes. It was found that polygons of official administrative units are more complex, i.e. irregular or elongated in shape than UGZs, indicating a more fragmented or heterogeneous structure. Additionally, the results indicated that the average relative difference between the areas of official administrative and the UGZs for all administrative centers was calculated to be 60.94%. Based on the UGZs and the raster population model of the B&H, a hierarchy of administrative centers of B&H was created. The hierarchy of centers according to UGZs was compared with the official data (population within regions and cantons). It was established that out of 16 administrative centers, 10 (62.5%) of them have the same hierarchical ranking, while the other six centers differ in only one rank of the hierarchy.

This study provides significant insights into the actual size of gravitational zones, reflecting the attraction power of regional centers in both individual and comparative contexts. It clearly illustrates that, for instance, Mostar has a considerably greater gravitational significance compared to Zenica or Bijeljina, despite having a smaller population. This discrepancy can be attributed to a range of factors, including a greater number of functions, better infrastructural status and the distance from other larger urban centers.

Brčko also registers a higher gravitational rank according to the derived model, which can be attributed to its exceptionally favorable transportation position, administrative-political status and the fact that, aside from Bijeljina, there is no larger or more functionally significant center in the northern border sector that could diminish its gravitational pull.

In future research, parameters for "mass" or the "attractiveness" of the city will be upgraded with data for the „functional“ mass of the city, which would best depict its gravitational attractiveness. This methodology can be applied to lower administrative levels, such as municipalities. The accuracy assessment of the derived models could be conducted by qualitative analysis.

The application of Huff model in optimizing administrative-territorial organization holds considerable promise, particularly given that competition among political units has often been more prevalent and documented than cooperation in numerous instances. Furthermore, the fragmentation of administrative units can result in duplication, inefficiencies of the system and higher costs. An important feature of Huff method is that it uses a spatial model with exact data (parameters) and formulas rather than subjective or political procedures.

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