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Accuracy Assessment of the Building Height Copernicus Data Layer: A Case Study of Bratislava, Slovakia

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Abstract: High buildings have generally changed the morphology of cities in recent decades, and they have a significant impact on multiple processes in the urban area. Building height is one of the criteria for urban land cover classification in local climate zone delineation and urban heat island modeling. The European Union's Earth observation program Copernicus aims to achieve a global, continuous, autonomous, high-quality, wide-range Earth observation capacity. One of the most recent Urban Atlas layers is the Building Height 2012 (BH2012) layer released in 2018, which consists of a 10 m resolution raster layer containing height information generated for core urban areas of the capitals of the EEA38 countries and the United Kingdom. This contribution aims to present the accuracy validation of the BH2012 data in Bratislava using the Slovak Basic Database for the Geographic Information System (ZB*GIS*). To compare the two datasets, four different tests were performed for the following group of landmark buildings: (i) with area > 100 m^2, (ii) in Urban Atlas classes with soil sealing > 10%, (iii) with height > 50 m, (iv) with area > 1 ha. The results demonstrate the effect of the building's area and compactness on the vertical accuracy of the BH2012 Copernicus data. The greater the building's area and compactness, the smaller the difference between its height value in BH2012 and *ZBGIS*. The Urban Atlas class 11100 Continuous Urban Fabric (soil sealing: >80%) recorded the lowest vertical accuracy. The BH2012 database provides sufficiently accurate data for primary planning analyses of public administration bodies and various stakeholders who need to obtain information on the nature of a locality for development activities and small-scale environmental analyses. However, for detailed studies focusing on the quality of life in cities at the local level, more precise identification of the building height is recommended.

Keywords: building height; Copernicus; accuracy; Bratislava; Slovakia

Citation: Szatmári, D.; Kopecká, M.; Feranec, J. Accuracy Assessment of the Building Height Copernicus Data Layer: A Case Study of Bratislava, Slovakia. *Land* **2022**, *11*, 590. https://doi.org/10.3390/land11040590

Academic Editor: Zhonghua Gou

Received: 14 March 2022
Accepted: 14 April 2022
Published: 18 April 2022

1. Introduction

The cities of the world are growing fast with increasing populations. The growth rates of urban areas depend upon the local culture, economy, climate, and other factors. High buildings have changed the morphology of cities in recent decades, and they have a significant impact on multiple processes in the urban area. They influence the microenvironment by casting shadows and blocking sunlight, exert significant demand on infrastructure and transportation systems, and affect the historic fabric, while reshaping the city's skyline, consuming massive energy, and requiring a high operational cost [1]. It is well known that the height of buildings affects the surrounding microclimate. The height of buildings influences wind movement as wind speed increases with height in the Urban Boundary Layer [2,3]. Natural ventilation efficiency is affected by variable factors, including wind movement around the buildings. Some studies have explained the effects of building height and porosity size on pedestrian level wind comfort [4]. Other microclimatic attributes affected by the canyon effect based on building height are the potential temperature, mean radiant temperature, and predicted mean vote distribution [5]. The building aspect ratio (building height to street width ratio) was confirmed to play an essential role in urban heating based on an air temperature simulation during different street canyon heating situations [6]. Building height variables also significantly impact the removal potential of ground-level pollutants in high-rise urban geometries [7]. Detailed analyses of the vertical profiles of pollutant concentrations showed that different diurnal heating scenarios could substantially affect the reactive gases exchange between the street canyon and air above, followed by respective dispersion and reaction. A higher building aspect ratio and stronger ambient wind speed were revealed to be, in general, responsible for enhanced entrainment of ozone concentrations into the street canyons along windward walls under all diurnal heating scenarios [8].

Recent design developments have shown a growing consideration of building height for microclimate interface as a part of a sustainable design strategy [9]. For example, in megacities, the land surface temperature decreases significantly with the increase in building height up to 66 m, because the increase in building height brings a significant cooling effect. When the height of the building exceeds 66 m, its impact on land surface temperature is gradually weakened due to the influence of building shadows, local wind disturbances, and building layout [10]. The quantitative relationship between the spatial variation of the building height and the associated albedo and land surface temperature change was also confirmed by [11]. Another design challenge is establishing the efficient height of buildings, which is defined as the height of a flat roof building when the flow around it most resembles the flow around a building with another shape [12]. Climatically responsive urban design enables individual buildings to make better use of natural energy; thus, it enhances the potential for pedestrian comfort [13].

Building height is one of the criteria for urban land cover classification in local climate zones delineation and urban heat island modeling [14–16]. Some studies have analyzed the environmental and bioclimatic factors that create microclimate relations between tall buildings the urban city fabric, and the distribution of the population [9,17,18]. Building height is also an indicator for estimating energy consumption [19], material stock allocation [20], and greenhouse gas emissions [21].

Obtaining insights into the dynamics of urban structure is crucial to the framing of the context within smart city concepts. Assessment of precise, fast, and up-to-date building and building floor data is essential for urban design, planning, management, and urban environmental studies. With the availability of high-resolution remote sensing imagery and multisource geospatial data, there is a great need to transform Earth observation data, including building height, into helpful information for different environmental analyses. Several research works have adopted methods for determining height using shadow in remotely sensed data, e.g., [22–25]. This approach classifies building shadows based on their relative within-scene characteristics and spatial context, rules for which are determined empirically against geolocated photographs of the study area. Alternatively, building height can be measured photogrammetrically analyzing stereo pairs of very-high-resolution optical satellite, aerial, or drone images [26,27] or by interferometric synthetic aperture radar (InSAR) techniques [28].

Another technique to estimate building height is represented by utilizing LiDAR data [29–31]. Recently, a study [32] aimed to develop a methodological framework to retrieve building height from ICESat-2 data (Ice, Cloud, and land Elevation Satellite) that employ photon-counting LiDAR to collect Earth surface elevation data globally.

The European Union's Earth observation program Copernicus aims to achieve a global, continuous, autonomous, high-quality, wide-range Earth observation capacity. Information from this program is provided through six thematic services: land, marine, atmosphere, climate change, emergency management, and security. Being part of the local component of the Land Service, the Urban Atlas provides pan-European comparable land cover and land use data for Functional Urban Areas. The Urban Atlas nomenclature includes 17 urban classes with a minimum mapping unit (MMU) of 0.25 ha and 10 rural classes with MMU 1 ha. The local component is coordinated by the European Environment Agency, which aims to provide specific and more detailed information that is complementary to the information obtained through the pan-European component. The local component focuses on different hotspots, i.e., areas prone to specific environmental challenges and problems based on very-high-resolution imagery (spatial resolution 2.5 m) in combination with other available datasets (high and medium resolution images) over the pan-European area. One of the most recent Urban Atlas layers is the Building Height 2012 (BH2012) layer released in 2018, which consists of a 10 m resolution raster layer containing height information generated for core urban areas of capitals of the EEA38 countries and the United Kingdom. Due to the possibilities mentioned above of using building height data, BH2012 provides wide opportunities for their use. However, studies using BH2012 data are so far limited, e.g., [33]. Precise and accurate building height maps are frequently required to track building construction speed, monitor horizontal and vertical urban growth and illegal constructions, update building records, prepare reasonable urban plans, assess hazard and risk, and generate infrastructure plans. This contribution aims to present the accuracy validation of the Building Height 2012 data in Bratislava using the Slovak Basic Database for the Geographic Information System (*ZBGIS*). The obtained results increase their information potential for various environmental analyses and assessments.

2. Data and Methods

The building height information in the BH2012 raster layer was derived from the Indian Remote Sensing Satellite-P5 (IRS-P5) stereo images of the reference year 2012 and derived datasets including the digital surface model (DSM), the digital terrain model, and the normalized DSM. It contains only the heights of the buildings itself (i.e., trees are masked out). The vertical accuracy according to the technical specification is 3 m.

In the case of Bratislava, the BH2012 raster layer is available for the city's whole administrative area. The downloaded zip archive per area included (i) the actual raster data in GeoTIFF format (ETRS89, Lambert azimuthal equal-area projection (LAEA)—EPSG: 3035); (ii) an XML-file with metadata; and (iii) a document with the results of quality checks. The size of the downloaded zip file of the BH2012 layer for Bratislava "SK001L1_BRATISLAVA_UA2012_DHM_v010.zip" was 1.23 MB. The size of the uncompressed actual raster layer (Figure 1) was 15.13 MB. The accuracy assessment for Bratislava included in the downloaded data was performed by the following methods: (1) accuracy assessment at building level, (2) accuracy assessment at building block level, and (3) accuracy assessment for landmark buildings (Table 1). The homogeneous spatial distribution of samples over the whole mapping area was achieved by splitting the mapping area using a reference grid with 2 km unit cell beforehand to set the condition not to select more than one sampling unit per grid cell. The reference input data were Google Earth Pro using 3D buildings and Street View mode and building footprints from Open Street Map (OSM) or extracted by means of visual interpretation from Google Earth imagery in case of OSM data unavailability. The quality level of the building heights was evaluated based on the following criteria:

Good (i.e., compliant with the technical specification, which is 3 m vertical accuracy);
Medium (i.e., out of the technical specification with an error between 3 and 6 m);
Poor (i.e., out of the technical specification with an error superior to 6 m).

Table 1. Results of quality checks of the BH2012 layer (included in the downloaded zip file).

Method	Evaluated Samples	Good	Medium	Poor
1	23	23	0	0
2 *	28	17	0	0
3	10	10	0	0

* No building to evaluate in 7 cases or no 3D or Street View available in 4 cases.

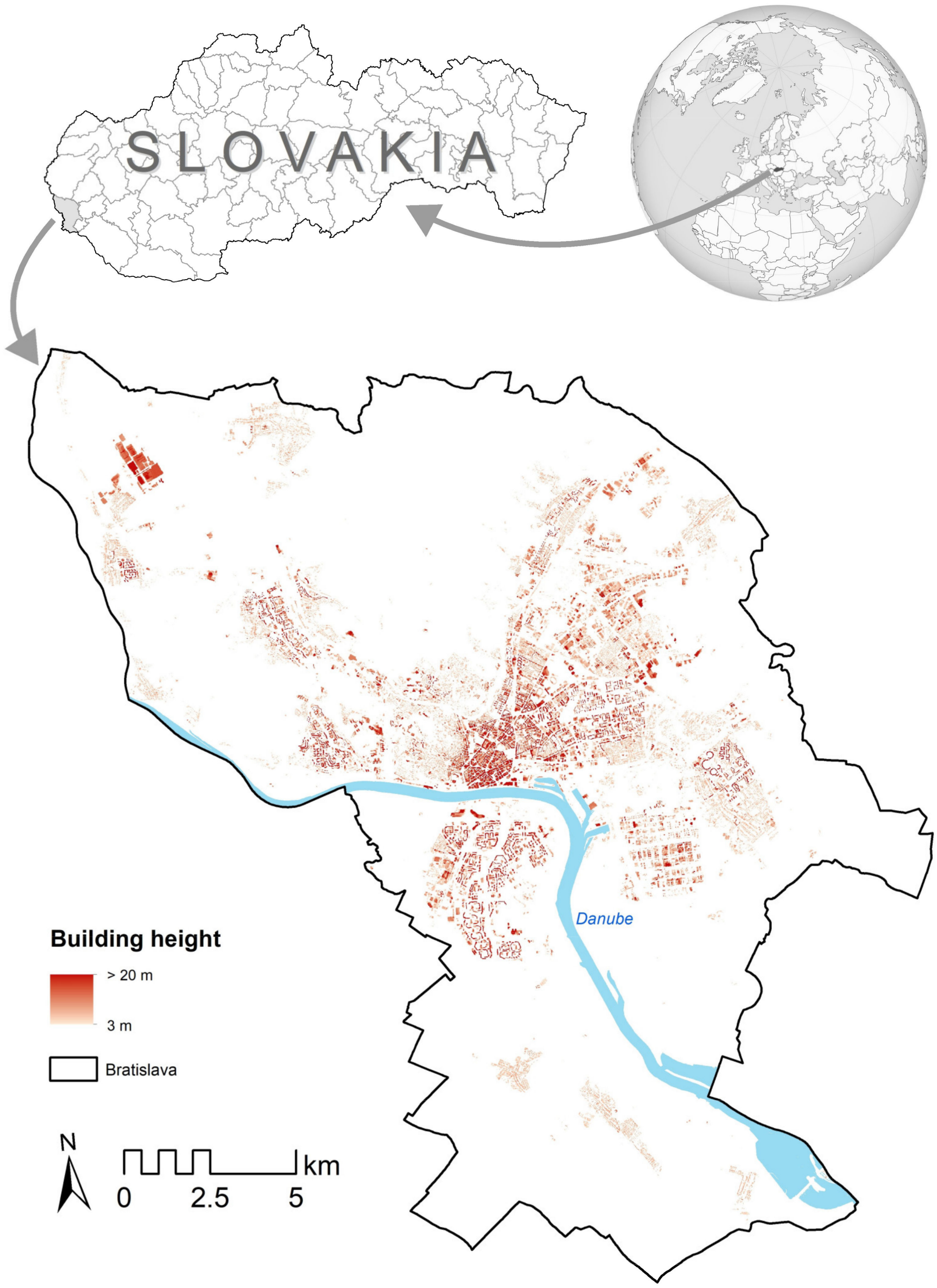

Figure 1. The BH2012 raster layer and the study area.

The aim of this paper is to provide a more detailed analysis of the BH2012 layer for Bratislava using the Slovak Basic Database for the Geographic Information System (ZB*GIS*), which is part of the Information System of Geodesy, Cartography, and Cadastre created and maintained by the *Geodesy, Cartography and Cadastre Authority of the Slovak Republic*.

ZB*GIS* is a spatial object-oriented database that is a reference basis of the National Spatial Data Infrastructure (a seamless geodatabase that covers the entire territory of the country). ZB*GIS* consists of data and metadata specified by Feature Catalogue (Catalogue of Objects Classes) which also defines the methods of their collection, geometry type, and their properties (attributes). The general attributes of a ZB*GIS* object are: ID—unique identifier, DOW—date of the last update, ACH—horizontal accuracy, ACV—vertical accuracy, etc. Visualization of ZB*GIS* data through map compositions is available via Map Client application. ZB*GIS* is maintained in the S-JTSK coordinate system (EPSG: 8352) and in the Baltic Vertical Datum after adjustment (EPSG: 8357). Features of the subcategory "AL015—Building" are defined as purpose-built objects made of various materials, different floor plans, heights, and shapes, intended for housing, cultural, social, administrative, legal, economic, and other purposes with a minimum area of 12 m^2. The building attributes obtained by processing of digital photogrammetric data (photogrammetric method), local investigation, together with the possibility of geodetic surveying of features or from the administrator are the following: AWP—navigation aids, BFC—type of use, EXS—object condition, HGT—height above the surface, LOC—location of the object, NAM—name, TXT—description, note. The declared horizontal and vertical accuracy of a ZB*GIS* building is, in the vast majority of cases (97%), up to 1 m.

The building height is measured from the base of the object to the highest point. In a building consisting of several parts of different heights but one type of use (BFC), the height of the whole building is considered to be its highest part, unless the height difference is more than 6 m. If the height difference is more than 6 m, the geometry of the building is divided. Different types of a single building are interpreted separately with their actual height. For buildings under construction, the height of the building is given only if the building has a completed roof, and its construction by height will not continue. Possible attribute values: a positive real number or −32767 (unknown) or −32768 (not applicable for ruins, e.g., Devín Castle). In the study area, ZB*GIS* data for the reference year 2012 contained a total of 91,354 buildings (features) with a maximum height of 114 m and an average height of 7.7 m (Table 2). The comparison of the datasets is shown in Figure 2.

Table 2. Number of buildings/features (ZB*GIS*) and raster cells with non-zero cell value (BH2012) in the study area.

Building Height Interval (m)	Buildings in ZB*GIS*	Raster Cells	Building Height Interval (m)	Buildings in ZB*GIS*	Raster Cells
0–9.9	72,750	208,977	60–69.9	24	243
10–19.9	12,005	63,618	70–79.9	19	100
20–29.9	4053	26,231	80–89.9	14	102
30–39.9	979	7637	90–99.9	3	57
40–49.9	650	4078	100 and more	5	81
50–59.9	21	358	−32,767 or −32,768	831	-

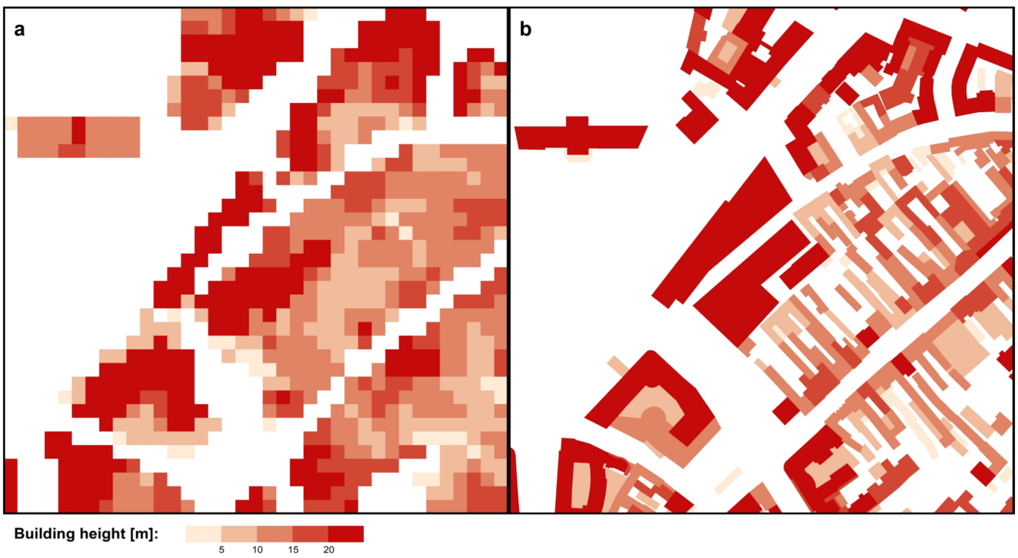

Figure 2. Comparison of the (**a**) BH2012 raster layer and the (**b**) ZB*GIS* subcategory "AL015—Building".

The data preprocessing consisted of selecting and exporting all the ZB*GIS* buildings for the study area and their transformation from S-JTSK to LAEA. Four tests for landmark buildings were used to compare the two datasets (Figure 3):

Test 1—Selection of buildings with area >100 m^2 (Shape_Area) and edge length > 10 m (Shape_Leng) and summarization of the values of the BH2012 raster within these polygons. All the zonal statistics (mean, majority, maximum, median, minimum, etc.) were calculated using the ArcGIS Desktop Spatial Analyst tool "Zonal Statistics as Table". For all the selected buildings (29,195), the difference between the ZB*GIS* height (HGT) and the average of all cell values (h_{BH}) in the BH2012 raster that belonged to these buildings was calculated:

$$\Delta h = \text{HGT} - \text{mean}(h_{BH}). \tag{1}$$

Test 2—The BH2012 raster cells were classified using the Urban Atlas nomenclature before the analysis, and the zonal statistics were calculated only for those buildings that belonged to artificial surfaces with soil sealing at least 10%, i.e., Urban Atlas classes: 11100 Continuous Urban Fabric (soil sealing: >80%), 11210 Discontinuous Dense Urban Fabric (soil sealing: 50–80%), 11220 Discontinuous Medium Density Urban Fabric (soil sealing: 30–50%), 11230 Discontinuous Low Density Urban Fabric (soil sealing: 10–30%), 12100 Industrial, commercial, public, military, and private units. For all the selected buildings (28,891), the height difference was calculated using (1).

Test 3—Selection of buildings with area > 100 m^2 (Shape_Area), edge length > 10 m (Shape_Leng), and height > 50 m (HGT). Using this condition, the forty tallest buildings in 2012 were selected. All the zonal statistics were calculated for all of them. Using this approach, both the vertical accuracy and geolocation accuracy were investigated during the detailed manual control of the ZB*GIS* and BH2012 layers. Because the building height (HGT) is defined by the ZB*GIS* from the base of the object to its highest point, the absolute height difference Δh was calculated as:

$$\Delta h = \text{HGT} - \max(h_{BH}). \tag{2}$$

Test 4—Selection of buildings with area > 10,000 m^2 (Shape_Area). The zonal statistics were calculated for the 52 largest buildings in 2012 (shopping malls, warehouses, factories, etc.). The vertical accuracy and geolocation accuracy were manually investigated, and the height difference Δh was calculated using the raster cell value that occurred most often of all the cells in the BH2012 raster that belonged to these buildings:

$$\Delta h = \text{HGT} - \text{mode}(h_{BH}). \tag{3}$$

The main advantages of the above-described tests in comparison with the official accuracy assessment (Table 1) is the robustness of the calculation (almost 30,000 investigated and evaluated objects by us vs. 28 selected sample units in the official report) and the use of high quality data obtained by photogrammetric image processing, local investigation, geodetic surveying, or from the building administrator as a standard. According to the official accuracy assessment, the quality level of the BH2012 raster was poor if the height difference was outside of the technical specification with an error greater than 6 m:

$$|\Delta h| > 6 \text{ m}. \tag{4}$$

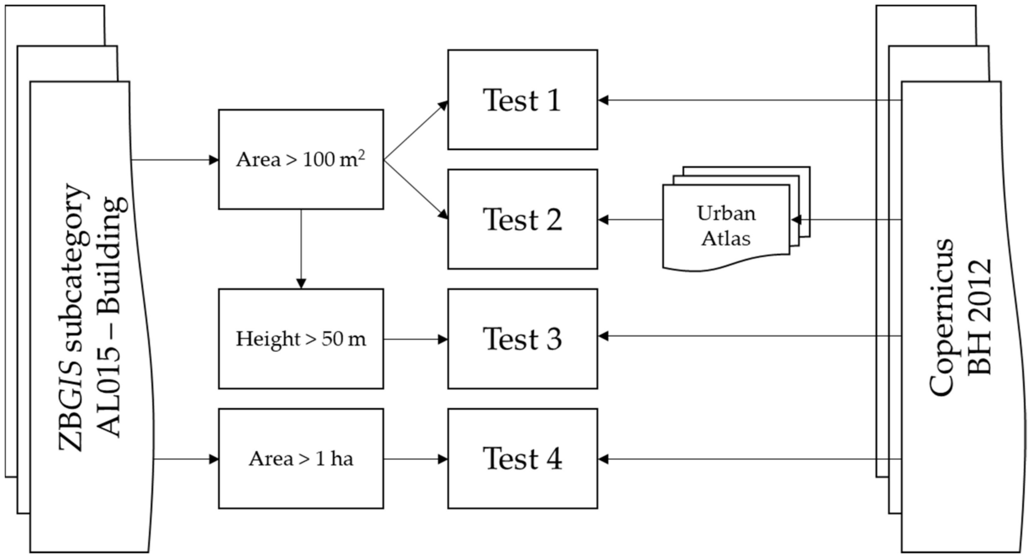

Figure 3. The research workflow.

3. Study Area

Bratislava, the capital of Slovakia, is situated in the extreme southwestern part of the country (Figure 1), where the Danube River has cut a gorge in the Little Carpathian Mountains at a tripoint between Slovakia, Austria, and Hungary. Due to its unique geographic location and special features, the city is faced with natural and political barriers for its spatial development. Bratislava has a permanent historically significant geostrategic and geopolitical position. It is located 65 km from Vienna, the capital of Austria and 193 km from Budapest, the capital city of Hungary. Bratislava has a very favorable transport-geographical position towards the Czech Republic too. The highway distance between Bratislava and Prague, the capital of Czechia, is about 300 km. It is also the country's largest city by population, although it is still one of the smallest capitals in Europe. According to a census in 2021, the city population was 475,503. The city has an area of 367.6 square kilometers (142 square miles), while the urban area is 123.7 sq km (48 sq mi). Thus, the population density is 1294 people per sq km.

The historical part of the city is dominated by its enormous castle, which stands on a plateau 100 m (300 ft) above the Danube. Among the historical buildings, St Martin's Cathedral is the largest and one of the oldest churches in Bratislava, known especially for being the coronation church of the Kingdom of Hungary between 1563 and 1830. The well-known Austro-Hungarian monarch, Maria Theresa, was crowned in this grand church. In 1936, the Manderla department store and residential building with a height of 45 m was considered an exceptionally tall building—at least for local conditions.

The period of socialism was characterized by the construction of housing estates with tall residential buildings, widely deployed throughout the Eastern Bloc during the communist era. A typical example is the district of Petržalka, situated on the right bank of the Danube. This district is primarily a residential area, with most people living in blocks of flats, a neologism for buildings built from concrete panels joined together to form the specific structure. As this city part was built primarily as a residential area, it has no clearly defined center. The highest building built in the period of socialism was the headquarters of Slovak Television (108 m). As an important road and rail junction and river port, Bratislava has diversified industries producing textiles, chemicals, metal, and electrical goods. The industrial and transport zones with high objects (e.g., chimneys and control towers) were situated mainly in the peripheral parts of the city.

The political changes in post-socialist countries of central and eastern Europe in 1989 increased the importance of the geographical location of Bratislava in relation to its development potential. The main factors of the development were identified by [34]:

The factor of settlement hierarchy;
The factor of macroposition attractiveness (so-called west–east gradient);
The factor of major transport infrastructure—highways and speedways, double-track electrified railways, airports, ports, and terminals of combined transport;
The diversified economy of the city;
Great human potential;
The status of the capital;
Historical and geographical evolution.

Bratislava has seen steady population growth throughout recent decades and is home to many corporations. The favorable conditions for entrepreneurs make it an ideal location for startup businesses. The result of the intensive developments has been an increase in high-rise buildings, representing both office and residential premises. Among the most important are the National Bank of Slovakia (114 m), Tower 115 (109 m), or the Eurovea Tower, which is expected to be finished in 2023 and aims to be the country's very first skyscraper with a height of 168 m.

4. Results

Four tests were conducted to evaluate the vertical accuracy of the BH2012 raster layer. In Test 1, 115,792 raster cells were included representing almost 30,000 buildings. In total, 5498 buildings were identified with a difference over 6 m between the two datasets (Table 3). The average difference in the building heights for both datasets is 2.56 m. Based on the results of the analysis, we can state that the vertical accuracy of the BH2012 raster layer in Bratislava is about 80%. In Test 2, the buildings in the Urban Atlas classes with different shares of soil sealing were compared. The highest error (22%) was identified in class 11100 (Continuous urban fabric) with predominant residential use: areas with a high degree of soil sealing. The lowest accuracy was identified in the group of the forty highest buildings over 50 m (Test 3). They were mainly administrative buildings (Table 4)—their location is shown in Figure 4. The size of the buildings plays an essential role in their unambiguous identification in relation to the size of the raster grid. The analyses of the largest buildings (Test 4) show a large building area leads to higher accuracy than the height of the object. Some examples of the validation are shown in Figure 5.

Table 3. Percentage of buildings with an error greater than 6 m between datasets.

	Raster Cells	Buildings	$\vert\Delta h\vert > 6$ m	%
Test 1				
Shape_Area > 100 m^2	115,792	29,195	5498	19%
Test 2				
UA class 11100	22,835	7786	1685	22%
UA class 11210	24,419	11,189	1897	17%
UA class 11220	2523	1480	219	15%
UA class 11230	229	171	33	19%
UA class 12100	62,551	8265	1434	17%
Test 3				
HGT > 50 m	707	40	12	30%
Test 4				
Shape_Area > 1 ha	12,599	52	12	23%

Table 4. Building height comparison for the forty highest buildings in 2012 in Bratislava (the address is indicated in italics in case of building name unavailability; a geolocation error identified on one occasion and vertical errors greater than 6 m are marked with ✖).

#	Landmark Building Name (or *Address*)	Type of Use	HGT [m]	max(h_{BH}) [m]	Δ*h*	Vertical Error	Geolocation Error
1	National Bank of Slovakia	bank	114	112	2		
2	Tower 115	administrative	109	112	−3		
3	Slovak Television Building	abandoned	108	108	0		
4	City Business Center I	administrative	103	104	−1		
5	Glória	residential	96	98	−2		
6	Aupark Tower	administrative	93	91	2		
7	VÚB headquarters	bank	89	100	−11	✖	
8	Myhive Vajnorská Tower 2	administrative	88	85	3		
9	St Martin's Cathedral	church	87	44	43	✖	
10	Incheba	congress and exposition centre	86	86	0		
11	Kukurica—Ministry of Defence SR	abandoned	84	87	−3		
12	Lakeside Park I	administrative	84	81	3		
13	Myhive Vajnorská Tower 1	administrative	82	81	1		
14	Rozadol	residential	81	66	15	✖	
15	Faculty of Civil Engineering, Slovak University of Technology	university	80	80	0		
16	TatraCity	administrative	77	77	0		
17	Technopol	administrative	73	69	4		
18	III Veže—Three Towers buildings	multifunctional	73	76	−3		
19	Westend Square	administrative	68	71	−3		
20	Westend Tower	administrative	68	52	16	✖	
21	Apollo Business Center II	administrative	68	67	1		
22	Slovak Radio Building	administrative	67	60	7	✖	
23	Universo	residential	67	64	3		
24	Dominant	residential	67	68	−1		
25	*Krasovského Street 13*	multifunctional	67	60	7	✖	✖
26	Bosákova IIIa	residential	65	63	2		
27	Blumenthal church	church	65	12	53	✖	
28	Hotel Kyjev	abandoned	63	65	−2		
29	*St Francis Square 18/A*	multifunctional	60	48	12	✖	
30	*Majerníkova Street 1/B*	residential	60	49	11	✖	
31	Ružinov University Hospital	hospital	56	59	−3		
32	Istropolis	multifunctional	55	45	10	✖	
33	Štúr youth hostel	hostel	54	51	3		
34	*Karadžičova Street 6*	residential	53	56	−3		
35	*Humenské námestie Square 4*	residential	53	58	−5		
36	Bratislava Castle	castle	52	39	13	✖	
37	BBC5	administrative	51	54	−3		
38	*Miletičova Street 46*	residential	51	51	0		
39	Pressburg Tower	administrative	50	50	0		
40	*Miletičova Street 1*	administrative	50	41	9	✖	

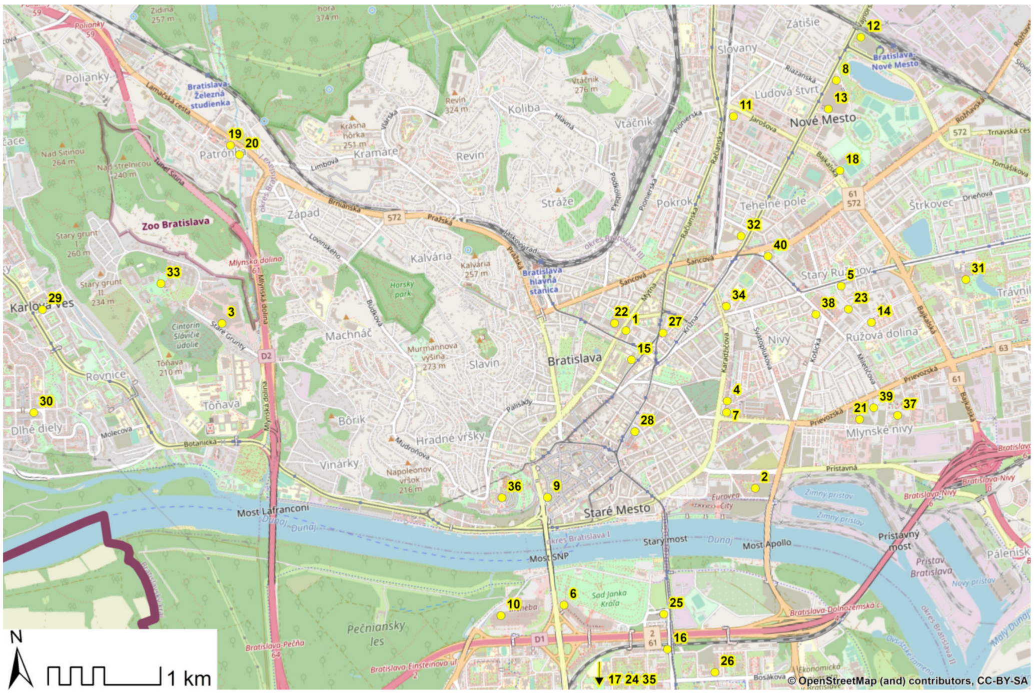

Figure 4. The location of buildings from Table 4.

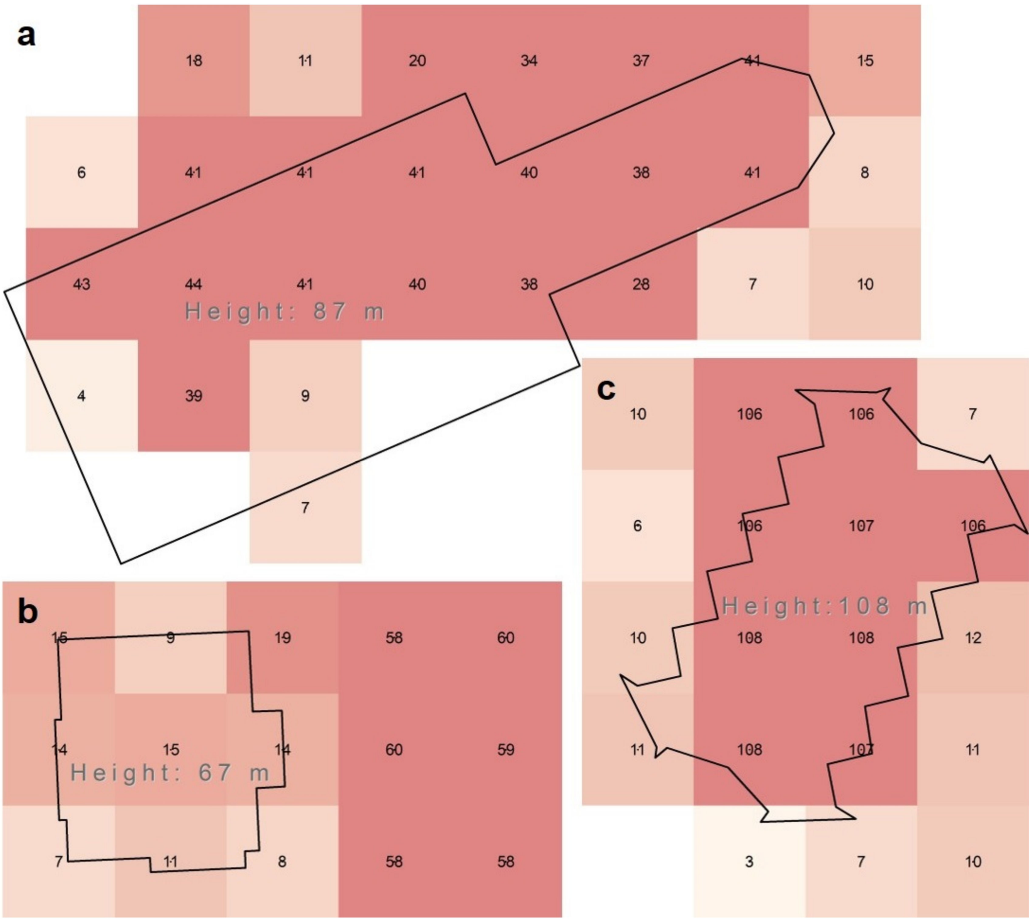

Figure 5. Validation examples: (**a**) St Martin's Cathedral—height difference 43 m, (**b**) multifunctional building located on Krasovského Street 13—height difference 7 m with geolocation error, (**c**) Slovak Television Building.

5. Discussion

The results quoted in Table 4 demonstrate the effect of the building's area and compactness on the vertical accuracy of the BH2012 Copernicus data which were compared with ZB*GIS* data related to the same reference year. The greater the building's area and compactness, the more pixels located in the area, giving a larger statistical sample, which causes a smaller difference between its height value in BH2012 and ZB*GIS*. For instance, the Three Towers buildings are 73 m tall according to ZB*GIS,* while according to BH2012, their height is 76 m. The difference is only 3 m. On the other hand, the height of St Martin's Cathedral tower according to ZB*GIS* and BH2012 is 87 m and 44 m, respectively. The difference here is as much as 43 m. Presumably, the buildings' vertical accuracy (especially those with small outline, such as church towers, chimneys, sightseeing towers) will increase using very-high-resolution satellite imagery [35,36].

Based on the comparison of the vertical accuracy of individual Urban Atlas land cover/land use classes, the imperviousness ratio did not significantly influence the vertical accuracy of the BH2012 data. However, the poorest accuracy corresponded to class 11100 (Table 3) with a soil sealing degree over 80%, part of which is the great heterogeneity of tall buildings.

This study can shed light on some theoretical discussions related to building height identification. Building height can be derived from a broad variety of geoinformation or remote sensing-based approaches, and some of them can predict building height more accurately than BH2012. The European Copernicus program encompasses the Sentinel-1 and Sentinel-2 constellations with a high potential for building height mapping [18]. Measuring building shadows is less reliable when the shadows overlap each other [37]. In this case, SAR side-looking geometry also caused adverse layover and shadow effects [28]. Photogrammetric height retrievals from aerial images are more accurate than those based on satellite images [38]. The accuracy assessment of the Copernicus BH2012 layer in the city of Warsaw showed the overestimation of the satellite-based building height by 1.08 m [39]. Despite other more precise approaches, the availability of the Copernicus Land Monitoring Service data in almost 800 European urban areas and BH2012 for core urban areas of capitals of the EEA38 countries and the United Kingdom guarantees that these data can be widely used in environmental analyses in those locations.

Previous research related to heat risk assessment in Bratislava [40] confirmed that building height over 20 m was the important factor for heat risk assessment as it concentrates more inhabitants, including an elderly population over 65, in a small area. Building height consequently reduces the role of the tree and grass vegetation which mitigates the risk index values.

The Atlas of risk-based vulnerability assessment of the impacts of climate change in Bratislava was prepared by the Office of the Chief Architect of the City of Bratislava [41]. The methodological procedure for determining the risks and vulnerabilities of urban systems includes various indicators, including the assessment of the sensitivity of buildings to heavy rainfall. The height of the buildings was not considered in this comprehensive study. The BH2012 data layer makes it possible to define more precise procedures for assessing the sensitivity to precipitation and other environmental factors (e.g., heat waves) related to climate change.

The cognition of human impacts on the landscape requires establishing research approaches that assess these phenomena on different levels. One of these is the land use and land cover accounting referred to by [42] as environmental accounting. Cognition of the accuracy of the BH2012 data layer will also promote its applicability in the frame of environmental accounting.

Height restriction laws often become a point of contention in cities due to their use in regulating housing supply growth. Regulation in many cities guarantees that buildings are not allowed to surpass the limited number of floors, or they cannot block the view of the important historical dominants. The General City Plan of Bratislava [43] determines permissible, restrictive, or prohibiting conditions for the use of particular areas and the intensity of their utilization. In addition to the basic regulations, such as the index of floor areas, the index of built-up areas, and the coefficient of greenery, the General City Plan also defines additional characteristics, including the area volume load index per hectare. This index indicates the intensity of land use, which expresses the ratio of the total construction volume of buildings (its above-ground and underground part) in m^3 to the entire area. When formulating the requirements for land use intensity, the particularities of individual urban units of the city territory are considered, including the building height. In the city center, the height of the building must respect the silhouette and take into account the nature of the environment; in the inner city, a combination of block, solitary, and high-rise development, including dominants, is accepted. In the outer city, the dominance of the housing function and low-rise development of family houses is expected. Up-to-date maps with accurate building height information can help identify problem areas where proposals to tighten regulations are required.

6. Conclusions

The territorial development of each locality is always conditioned by factors that may affect the optimal intensity of land use determined on the basis of the type of urban function. Territorial regulations define characteristics that can have a decisive influence on the final character of the urban development in a given area, including the height of buildings. Regarding the connection of the new development to the original structure, it is necessary to subordinate the new buildings to the character of the existing building structure in the given area, especially in the historical city centers. The new BH2012 layer has enriched the option of its use in the assessment of different aspects of the urban landscape. The database provides sufficiently accurate data for the needs of primary planning analyses of public administration bodies and various stakeholders who need to obtain information on the nature of a locality for development activities. Four different tests showed that an error larger than 6 m fell within the interval 17–30%. This accuracy is considered to be sufficient for small scale environmental analyses. However, for detailed studies focusing on the quality of life in cities at the local level, more precise identification of the building height is recommended.

Author Contributions: Conceptualization, D.S., M.K. and J.F.; methodology, D.S.; formal analysis, D.S.; writing—original draft preparation, M.K., D.S. and J.F.; writing—review and editing, M.K., D.S. and J.F.; visualization, D.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Slovak Scientific Grant Agency VEGA under Grant 2/0023/19, "Land cover dynamics as indicator of changes in landscape".

Informed Consent Statement: Not applicable.

Data Availability Statement: The Building Height 2012 (BH2012) raster layer can be downloaded directly from Copernicus (https://land.copernicus.eu/local/urban-atlas/building-height-2012 (accessed on 2 December 2021). *ZBGIS* data are available via the Map Client (https://zbgis.skgeodesy.sk accessed on 2 December 2021).

Conflicts of Interest: The authors declare no conflict of interest.

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