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Estimating the Impact of Agricultural Land Use – Land Cover Change on Riverbank Stability and Critical Inland Navigation Areas of the Danube River

Maxim Arseni [1,2], Valentina-Andreea Calmuc [2,*], Madalina Calmuc [2], Laureana Odajiu [3], Silvius Stanciu [3] and Lucian-Puiu Georgescu [1,2]

[1] Department of Chemistry, Physics and Environment, Faculty of Sciences and Environment, "Dunarea de Jos" University of Galati, 800201, Galati, Romania

[2] REXDAN Research Infrastructure, "Dunarea de Jos" University, Galati, 800008 Galati, Romania

[3] Faculty of Food Science and Engineering, "Dunarea de Jos ˘ " University of Galați, 800008, Galați, Romania

* Correspondence: valentina.calmuc@ugal.ro

Abstract

Intensive agriculture, deforestation, and frequent land-use changes contribute to increased soil erosion and sediment transport from both arable and non-arable lands into minor river channels. These factors directly and indirectly influence riverbank erosion and, in turn, sediment transport in rivers. Evidence on anthropogenic land-use/land-cover (LULC) change impact remains limited in both quantitative and spatial terms within the Danube River Basin. The results based on the combination of LU-LC products derived from the Copernicus satellite (year 2000 vs. year 2018) and validated in the field by UAV flights (year 2025) indicate that land conversion from riparian vegetation to cultivated or uncultivated lands reduces the root cohesion and soil–bank structural stability, thus increasing sediment sediment delivery to the river channel through overland flow, and favors bank failure where agriculture is in the immediate vicinity of the banks. The workflow proposed in this study offers a transferable and adaptable solution for areas with similar characteristics for a multitemporal approach regarding the influence of especially agricultural lands on sediment transport and riverbank erosion.

Keywords: agriculture; land use land cover; sediment transport; Copernicus satellite; bank erosion; LU-LC change maps

1. Introduction

The Danube River Basin is one of the most complex river ecosystems in Europe. It is constantly undergoing morphological transformations driven by both natural processes and anthropogenic interventions [1]. Among the most prominent processes are bank erosion, bed erosion and aggradation, changes in the riverbed, as well as the imbalance of sediment quantities. The unevenly distributed amount of sediment affects navigation, flood protection, biodiversity, and the overall stability of the river corridor. Aquatic habitats are generally affected by sediment transport. Sediments, in turn, have a direct impact on the hydrological regime of the Danube River by modifying turbidity, light penetration, water temperature, and dissolved-oxygen availability [2]. However, there is also an indirect negative effect, as sediments are effective carriers of pollutants adsorbed in the running water network [3,4]. Subsequently, these pollutants are transferred in the aquatic food chain, with toxic impact on fish and finally on humans [5].

The identification and monitoring of areas vulnerable to accelerated and excessive erosion thus become an essential condition for sustainable sediment management, in line with the EU Strategy for the Danube Region and the EU Mission "Restoring oceans and waters by 2030". A series of studies identified in the literature highlights several new sectors prone to erosion, especially on the Lower Danube.

At the same time, there is a direct connection between excessive erosion on the Danube River and agricultural areas near the banks. When the–runoff increases, the water infiltration capacity decreases. Thus, the rain turns into an accelerated surface flow, with a tendency to move towards the river banks and increase their erosion [6,7].

If there is also a lack of riparian vegetation or buffer strips, the soil can be easily transported by the wind to the banks, resulting in new sand deposits. This lack of vegetation also leads to accentuated bank breaks, not being stabilized by the roots of trees, shrubs, or vegetation [8].

Another factor directly connected with agricultural lands, or those intended for grazing, is the anthropogenic activity of intensive grazing in the vicinity of the banks. This activity destroys the vegetation cover and induces land instability in the area of the Danube River banks.

In addition, the quality of river sediments is also impacted by intensive agricultural activity in the area directly adjacent to a river. Agrochemicals lead to the transport of pollutants through groundwater directly from agricultural lands to the minor riverbed [9]. Thus, the transported sediments (first from the banks, then into the thalweg) become carriers of pollutants from one area to another along a river.

River erosion is also favored by agricultural soil that is not cultivated or is left uncovered. During periods of drought and strong winds, the wind directly transports dust in the form of PM_{10} and $PM_{2.5}$ through the atmosphere. In practice, some of the dust from unused agricultural land not only ends up in the river but is transformed into aerosols that degrade air quality [10,11]. Wind erosion also transports organic carbon into the running water, which decomposes and amplifies CO_2 emissions, and in certain areas, it can also form CH_4 (methane). If this process also involves the burning of stubble or plant debris, the impact doubles: on the one hand, direct emissions of $PM_{2.5}$, CO, NO_x, and volatile organic compounds occur, and on the other hand, the land remains unprotected, which amplifies erosion at the first rainfall events and accelerates the supply of sediments and nutrients to the river [12,13].

All these erosion phenomena, whether from agricultural lands to the minor riverbed, or whether they are erosion of the bank or navigable channel, lead to accentuated migrations of sediment deposits and can favor flooding in certain critical sectors over time, or can disadvantage river navigation, as the reduced river navigation on the Danube in the Corabia - Turnu Magurele sector, Romania.

At the EU level, there are several projects that analyse in detail the sedimentation and erosion rates on the Danube River. Therefore, the ICPDR documentation [14] on sediment regime modification in the Danube River Basin Management identifies land-use correlation and river basin management as important factors. This means that information on agricultural land use is needed in sediment transport or storage assessments.

Large-scale sedimentation and erosion trends are well defined in the DanubeSediment Project [15]. Nevertheless, the local variability of these processes remains insufficiently resolved, especially in the Lower Danube (Figure 1).

The identification of hotspots, such as rapidly eroding banks or localized sediment deposits, in terms of small-scale sediment dynamics is limited by the lack of data on sediment transport and recent morphological changes mentioned in Figure 1. Another important EU project that implements a harmonized approach to sample collection and a robust sediment analysis methodology is the SIMONA Project [16]. SIMONA does not capture the full diversity of hydromorphological conditions along the entire Danube River due to the limited number of stations per country.

As a result, potential hotspots influenced by navigation, agriculture, or recent engineering works overlap with the DanubeSediment Project.

Figure 1. Stations in the Romanian sector studied through major EU projects.

Understanding land use and land cover (LU-LC) dynamics along the Romanian sector of the Danube River is critical for integrated river-basin management, sediment budget analyses, hydromorphological assessments, and environmental planning. Although major EU-funded initiatives over the past decade - such as sediment monitoring and hydromorphological mapping - have generated valuable insights, substantial spatial gaps persist (Table S1). These gaps largely stem from insufficient data on erosion processes and the influence of agricultural areas adjacent to watercourses on bank modification and erosion. Such limitations are especially evident in the major riverbed or floodplain area of the Danube River, as well as in agricultural areas where field validation has historically not been performed. In these areas, an analysis of satellite LU-LC changes over time and space is mandatory. In the critical navigation points on the Romanian sector, such an analysis is completely missing. There are no studies demonstrating agricultural land changes or LU-LC changes in correlation with erosion and sedimentation processes near the banks of the Danube River. There is only a series of sediment sampling activities from critical navigation points, and the intensity of erosion mentioned (Figure 2).

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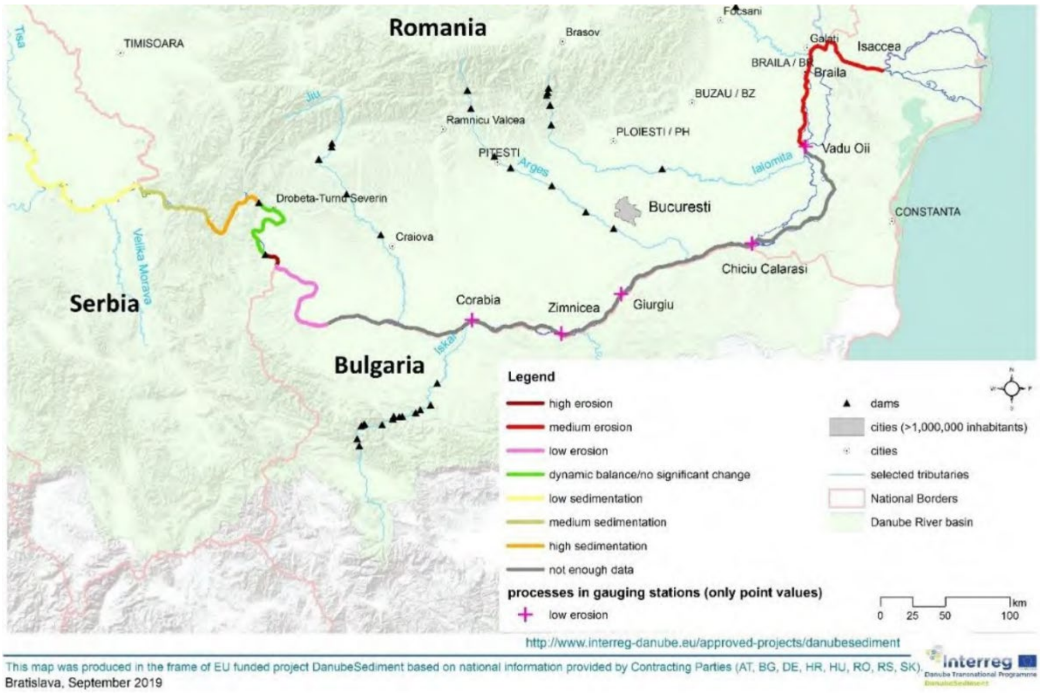

Figure 2. Map of the main trends of the river processes (erosion/sedimentation) prevailing along the Lower Danube [17].

To fill the knowledge gaps, a focused satellite investigation was performed using two comparable LU-LC datasets representing the years 2000 and 2018 on Romanian Lower Danube River sector. The analyzed areas were selected based on the critical points identified in previous studies under the Danube Sediment and SIMONA projects for the Romanian part of the Danube River, where "low erosion" – pink line, and "not enough data" – gray line, are indicated (Figure 2).

This study aims to present a workflow and analysis on the use of harmonized Copernicus land cover datasets (2000 vs 2018 years) to quantify LU-LC change around known hotspots of the Lower Danube and to validate these results using precision UAV flights. This study is useful for interpreting how land use changes, especially agricultural land, in the immediate vicinity of a river, in this case the Danube River, can contribute to observed erosion–sediment dynamics, improving the evidence base for monitoring and sediment management actions.

2. Materials and Methods

The choice of the 2018 LU-LC dataset was strategic: a first test analysing the data between 2018 and 2016, we find that land cover change is minor (<1%), allowing 2018 to serve as a reliable actual reference point. Likewise, the year 2000 represents a past-time baseline period preceding major agricultural reforms, land restitution processes, and EU alignment measures that have influenced land management dynamics [18,19].

Copernicus satellite images of LU-LC changes were used as a harmonized, medium-resolution land information product generated under the Copernicus Land Monitoring Service [20].

It integrates satellite imagery—primarily from the Sentinel-1 and Sentinel-2 constellations—with advanced classification algorithms to produce detailed, consistent land-use and land-cover layers across Europe [21,22]. The dataset provides information on natural surfaces (forests, grasslands, wetlands), agricultural zones, artificial surfaces, and water bodies. The LU-LC derived from Copernicus emphasizes temporal consistency, offering multi-year series suitable for long-term change analysis [23,24]. The most recent fully processed and released reference for Copernicus LU-LC datasets is 2018, which marks the final year with complete, validated pan-European LU-LC coverage in the current dataset cycle. These data were finally validated in 2020. Copernicus also provides products for 2019-2021, but only for specific thematic layers (forests, urban areas, climate

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changes); however, 2018 is the last year of the harmonized, full LU-LC status layer used for many scientific comparisons, especially for analyses of changes in agricultural areas.

The analysis of land use changes with validation of field data obtained from UAV flights was carried out following the steps in the experimental flow presented in Figure 3. The research study, which utilizes Sentinel-2 satellite imagery for LU-LC and NDVI change dynamics for Gelephu, Bhutan, developed by Tempa (2024) [25], is based on similar activities represented in the Figure 3 flowchart. This represents a universal, scalable, and applicable experimental flow for any region or area to be studied in this context.

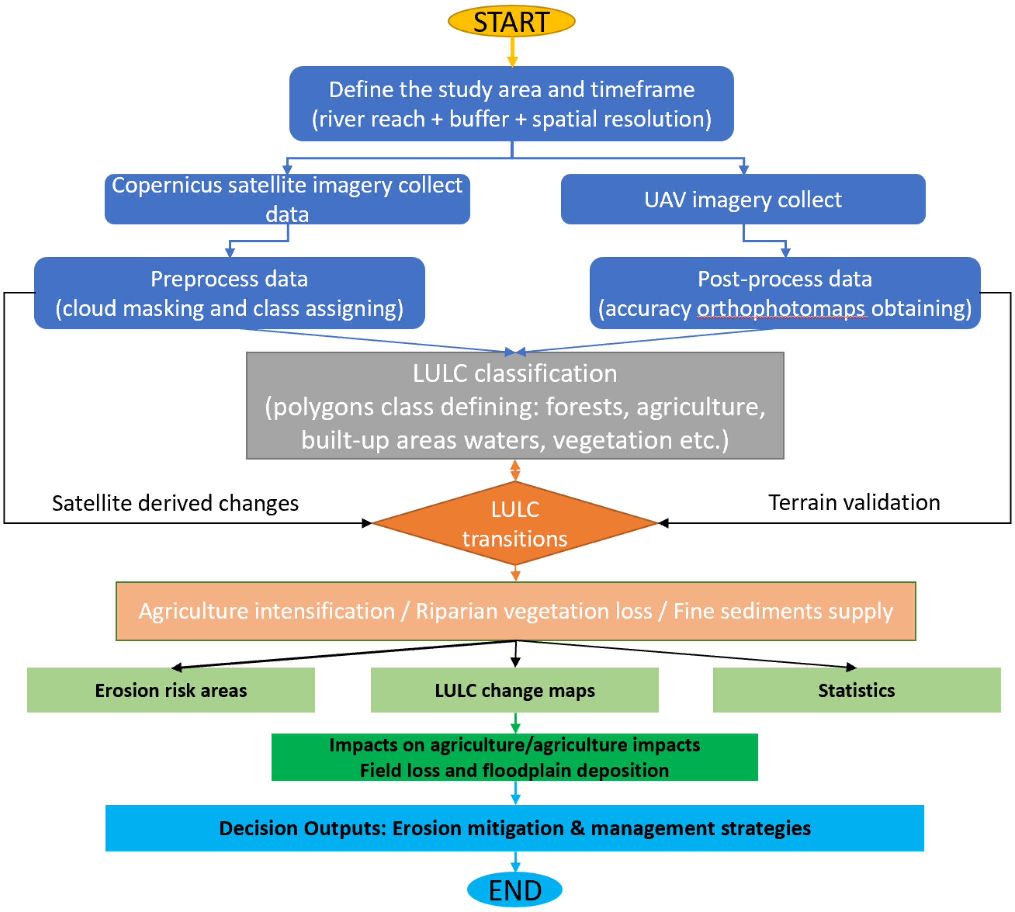

Figure 3. Integrated workflow based on the analysis of Copernicus LU-LC data (period 2000–2018), correlating riparian buffer zone change, bank stability, and shoreline migration with validation through erosion–deposition mapping and sediment transport potential related to agricultural areas.

2.1. Satellite-Derived Data

To achieve the main purpose of these analyses, first of all, a standardized 20x20 km polygon mask was used to frame each area of interest. According to Ren (2022) and Ye (2023), this spatial window ensures that each extracted subset covers a sufficiently large portion of the Danube floodplain, adjacent terraces, agricultural fields, wetlands, and riparian zones [26,27]. The goal was to capture not only localized changes but also broader landscape transitions that can influence sediment connectivity and hydromorphological behavior (Figure 4).

The mask or 20x20 km polygon was placed to maximize inclusion of relevant geomorphological features, such as: active and abandoned floodplain channels, agricultural areas, pasture zones and shrubland, riparian forests, water bodies linked to Danube dynamics system, etc.

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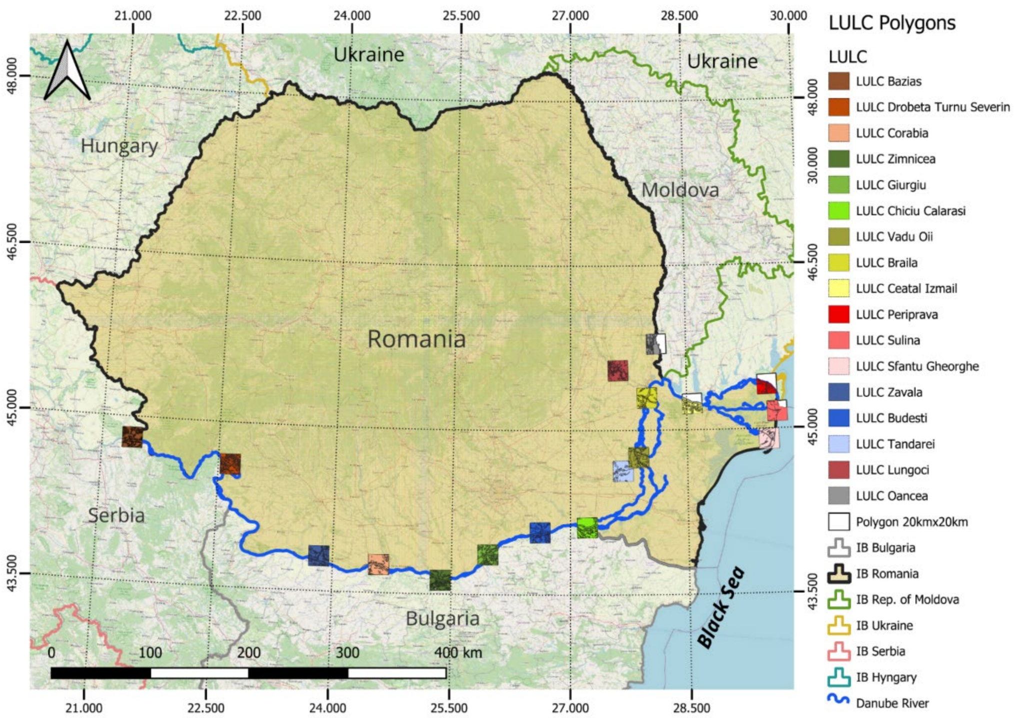

Figure 4. The defined 20 × 20 km polygon mask for LU-LC extraction at critical points in the Lower Danube River.

Before any temporal comparison, the two LU-LC datasets from 2000 and 2018 were reprojected into a unified projection (typically an international EU coordinate system or UTM 35N). This ensures that pixel alignment is accurate across years. To correctly identify similarities or changes in LU-LC between those two periods at critical points in the Lower Danube River sector, it is important to use harmonized classification symbology. Even when datasets appear similar, the exact class definitions may vary. A mapping table was created to harmonize categories, merging them into the following core groups: *Continuous and Discontinuous urban fabric, Industrial or commercial units, Road and rail networks and associated land, Port areas, Airports, Mineral extraction sites, Dump sites, Construction sites, Green urban areas, Sport and leisure facilities, Non-irrigated arable land, Rice fields, Vineyards, Fruit trees and berry plantations, Pastures, Complex cultivation patterns, Land principally occupied by agriculture with significant areas of natural vegetation, Agro-forestry areas, Broad-leaved forest, Coniferous forest, Mixed forest, Natural grasslands, Transitional woodland-shrub, Beaches - dunes – sands, Bare rocks, Sparsely vegetated areas, Inland marshes, Water courses, Water bodies, Sea and ocean.*

Once the datasets were perfectly aligned, a pixel-based change detection workflow was implemented. The principle is based on pixel change detection [28]:

$$Change\ (I) = LULC_{2018}(i) - LULC_{2000}(i) \qquad (1)$$

This comparison allows for the identification of stable areas (same class in 2000 and 2018) and transitional areas (class switched from one category to another). A change matrix was generated. This generated matrix quantifies how much agricultural land in 2000 remained agricultural in 2018, how much agricultural land transformed into grassland or built-up zones, how many wetland pixels were lost or gained, and how much forest area transitioned to other categories. This matrix forms the foundation for interpreting temporal LU-LC dynamics.

GIS-based preparation and LU-LC area calculations are essential because accurate mapping of agricultural expansion or contraction directly informs how soil erosion and runoff contribute to river sedimentation [29,30]. Agriculture often increases exposed soil, accelerates surface flow, and transports nutrients and sediments into waterways. By quantifying land-cover changes through GIS, we link spatial patterns of farmland with erosion hotspots, identify where sediment loads are likely

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increasing, and assess long-term impacts on river morphology, navigation, and flood risk. Thus, precise GIS analysis provides the evidence base needed for sediment-management and sustainable land-use planning.

At the same time, a numerical calculation was applied. Each LU-LC dataset for all 17 critical points on the Lower Danube River was converted to a shape polygon type. For each polygon, a terrain class type was assigned. The area was calculated for each terrain type polygon. The calculation differs from counting pixels for several reasons: the area from pixel depends directly on the dimension of the pixel, and is quantized into square cells. To calculate the area of an irregular polygon, the entire pixel size is quantified. Edge pixels are counted as full area, even if they are only partially covered. In the case of shape calculation, it is a geometry-based mathematical formula that follows exact topology. The area is calculated based on each vertex of the polygon shape, most often by a background Voronoi polygon separation. Taking these factors into account, the shape polygon area calculation using the first method is overestimated or underestimated. After these, the numerical comparison was achieved by the difference between the first 2018 and the second 2000 LU-LC datasets. This approach provides not only aggregate trends but also site-specific insights into spatial heterogeneity along the river.

From a process perspective, these results are essential for understanding the interaction between land use and fluvial dynamics. Agricultural expansion, especially in proximity to riverbanks, is often associated with reduced vegetation cover, soil compaction, and increased surface runoff, which can intensify bank erosion and sediment delivery to the channel. On the other hand, preserving or restoring near fluvial forests and wetlands-improves the bank's stability. These actions also increase the retention of sediments and can reduce the flood hazard peaks. Agricultural land-use change (LU-LC) within large river corridors reflects both natural geomorphological dynamics and anthropogenic pressures. Along the Lower Danube, the sectors near Baziaș, Drobeta-Turnu Severin, and Corabia represent distinct physiographic units shaped by variable hydrology, floodplain width, sediment supply, and land management strategies.

2.2. UAV Survey Methods and Data

The UAV (Unmanned Aerial Vehicle) survey was performed in 2025 in an agricultural area to validate the LU-LC results from 2018. These images, with an improved resolution, are important for assessing the differences in LU-LC. It serves as a field validation. The survey covers the surface for the Corabia critical point, starting from the Danube River to upstream of the polygon boundary. Due to the impossibility of surveying in the Bulgarian section, the validation was performed only-in the Romanian area.

The validation of land use and land cover (LU-LC) results is one of the essential steps in spatial analysis, environmental monitoring, and assessment of changes occurring over a certain time interval [31,32]. In the context of the study carried out in the critical area of Corabia, the use of a UAV flight in 2025 allowed the verification and confirmation of the classifications obtained in 2018, based on Copernicus data.

This validation process is particularly important because satellite images, although having extensive spatial coverage and being standardized at the European level, have limitations regarding resolution, classification accuracy, and fine identification of objects at a local scale. UAV flights currently represent sufficiently modern technology for validating LU-LC results due to their high spatial resolution, on the order of centimeters, and flexibility in mission planning (Figure 5).

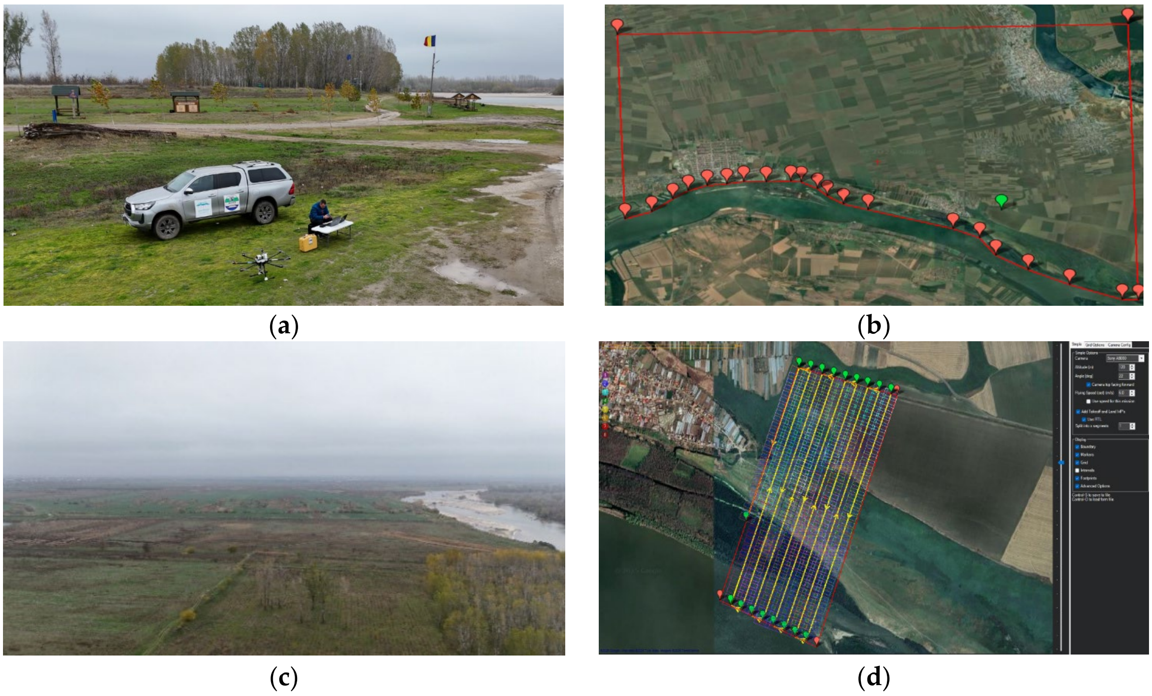

Figure 5. Field deployment: (a) UAV flight boundary for LU-LC validation of the entire area (Corabia–Turnu Măgurele case study); (b) example of aerial imagery for LU-LC assessment; (c) UAV single-flight path capacity.

The UAV flight covered 21,220.00 ha (Figure 5b), with a total flight time of 152 hours. From the UAV field survey, 64,321 images were recorded. Because the used surveyed drone can cover in one flight no more than 35 minutes of flight (depending on wind speed, and air temperature) at 120 m altitude above the ground (AGL), it was done approximately 270 flights, during 26 days (Figure 5d). The 50% x 50% overlapping and sidelapping of footprints was used. This was sufficient to obtain an accurate 0.5 x 0.5 m/px orthophotomap of the entire validation area [33]. The flights were done only on the Romanian Danube River floodplain, because the Bulgarian part was restricted from a UAV flight point of view.

3. Results and Discussion

3.1. Results and Discussion Related to Satellite-Derived Data

The satellite data obtained from Copernicus were compared in terms of LU-LC changes between the two periods: 2000 versus 2018. The results were analyzed in terms of the areas mainly covered by agriculture, the disappearance of some plots over time, or their appearance from one period to another. The results presented in Figures 6-11 show essential changes in land use, especially in the areas adjacent to the Danube River.

Figure 6a, b shows that **the Baziaș sector** represents the entrance of the Danube into Romania, characterized by a transition from narrow, confined valleys to a widening floodplain. The LU-LC maps indicate that non-irrigated arable land (class 211) shows a moderate reduction between 2000 and 2018. Pastures (231) appear partially replaced by heterogeneous agricultural areas (242), reflecting agricultural intensification or parcel restructuring. Complex cultivation patterns (242) increase, indicating a shift toward mixed-use agricultural parcels. Expansion of urban fabric (111–112) is minor but noticeable in proximity of local infrastructure (Figure 6b). The numerical data show a marked increase in arable land (+5.99%) and pastures (+1.96%), while heterogeneous agricultural areas (–5.45%, –5.09%) and vineyards/orchards clearly declined (Figure 6c).

Forest classes increased moderately (+2.63%). Wetlands and riparian vegetation show minor losses. Overall, agriculture consolidates into large arable blocks.

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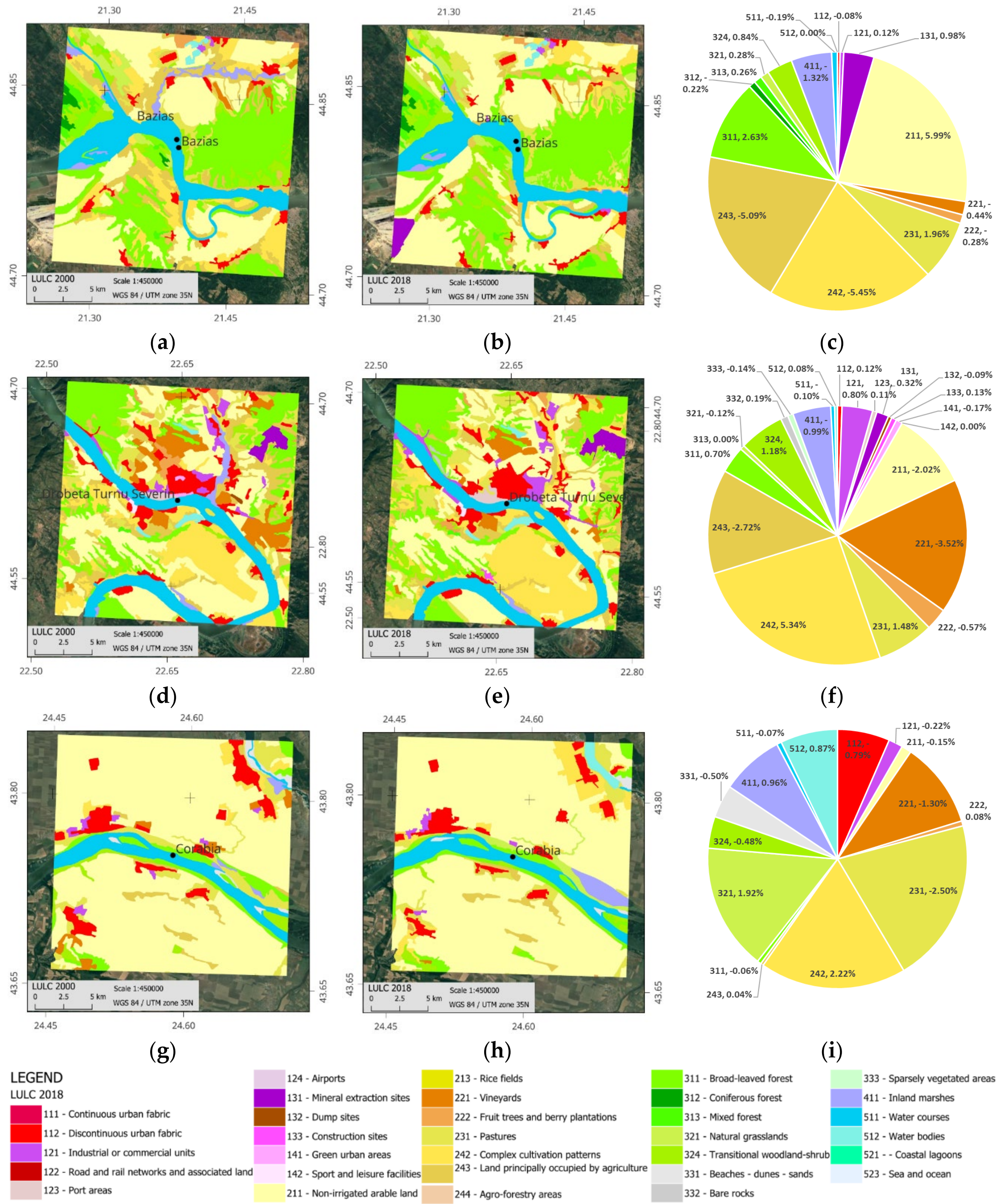

Figure 6. Geospatial and temporal changes of LU-LC 2000 (a, d, g) vs. LU-LC 2018 (b, e, h) at the Baziaș, Drobeta Turnu Severin, and Corabia observation areas. The pie charts represent the percentage changes between the years 2000 and 2018 (c, f, i).

The Drobeta-Turnu Severin zone lies downstream of the Iron Gates reservoir, within a highly modified hydrosystem. The terrain in this area is characterized by a floodplain with very low slopes over most of the surface, but near the banks, there are also steep terraces with slopes that are locally stabilized by stone dikes [34]. The maps in Figure 6d,e show a representative expansion of artificial surfaces (111–121) associated with urban growth and industrial infrastructure. The results also indicate a decrease in non-irrigated arable land near the city, with agricultural production expanding outward and an increase in heterogeneous agricultural areas (242), likely due to peri-urban land-use diversification. A reduction of natural grasslands (321–324) was assessed, partially replaced by agriculture or built-up areas (Figure 6e). The land-cover statistics for Drobeta-Turnu Severin indicate an important reconfiguration of surface types between 2000 and 2018. Artificial surfaces show consistent expansion across all subclasses (112, 121, 123, 131), reflecting continued urbanisation and infrastructure development. Simultaneously, significant reductions in arable land (–848.8 ha) and permanent crops, particularly vineyards and orchards (–1474.8 ha; –238.7 ha), demonstrate a pronounced decline in traditional agricultural systems within the peri-urban zone (Figure 6f). In contrast, the strong increase in pastures (+622.5 ha) and heterogeneous agricultural areas (+2,240.5 ha) suggests fragmentation and diversification of agricultural practices, likely driven by land abandonment, a clue toward mixed cultivation, or conversion of larger parcels into smaller multifunctional units. Forest and transitional woodland–shrub classes also increase moderately, indicating successional processes on marginal riverbank land. Wetlands, riparian vegetation, and inland water surfaces show minor diminution, consistent with local hydrological regulation.

Corabia area (Figure 6g), located in the Romanian–Bulgarian Danube floodplain, represents one of the widest and most intensively cultivated floodplain sectors [35]. The LU-LC maps indicate a large expansion of non-irrigated arable land (211) between 2000 and 2018 (Figure 6h). In the Corabia sector, built-up areas (112) decrease by 336.8 ha (-0.79%), and industrial areas (121) by 91.5 ha (-0.22%). Arable land (211) remains almost constant, with a minimal reduction of 63.8 ha (-0.15%). Permanent crops (221) register a severe decrease of 554 ha (-1.30%), and pastures (231) decrease by 1064 ha (-2.50%). In contrast, heterogeneous agriculture (242) increases by 942 ha (+2.22%), and natural grass vegetation (321) increases by 815 ha (+1.92%). Wetlands (411) increase by 406.6 ha (+0.96%) (Figure 6i).

Figure 7 shows the results of the LU-LC comparison at the **Zimnicea observation point**. Agricultural land remains a dominant type os land but indicates a decline in other categories. Notably, non-irrigated arable land (211) decreased by approximately 733 ha (-1.73%), while rice fields (213) and beaches–dunes–sands (331) present in 2000 were completely absent in 2018, indicating either land abandonment or reconversion (Figure 7a,b). Pastures (231) and complex cultivation patterns (242) increased (+860 ha and +648 ha, respectively), suggesting agricultural diversification and a shift toward mixed or less intensive land-use. At the same time, semi-natural and transitional classes expanded. Transitional woodland–shrub (324) increased by over 700 ha (+1.66%), while inland marshes (411) nearly doubled (+406 ha), pointing to local wetland regeneration or reduced drainage intensity. Instead, broad-leaved forest (311) declined by about 560 ha (-1.32%), which may reduce long-term bank stability and sediment retention capacity. Minor changes in watercourses (511) and water bodies (512) indicate relative hydrological stability at the class level (Figure 7c).

The Giurgiu area (Figure 7d,e) indicates urban-related classes with mixed trends: discontinuous urban fabric (112) expanded by more than 450 ha (+1.08%), while continuous urban fabric (111) and industrial or commercial units (121, 122) declined, suggesting urban sprawl rather than densification. The appearance and growth of mineral extraction sites (131) and dump sites (132) point to localized infrastructure and resource-use pressures. Agricultural land indicates the most pronounced changes. Non-irrigated arable land (211) underwent a significant reduction of over 2,100 ha (-5.07%), accompanied by a strong reduction of pastures (231) (Figure 7f). Non-irrigated arable land was reduced by more than 2,100 ha, accompanied by a substantial reduction in broad-leaved forests (approximately −1,000 ha).

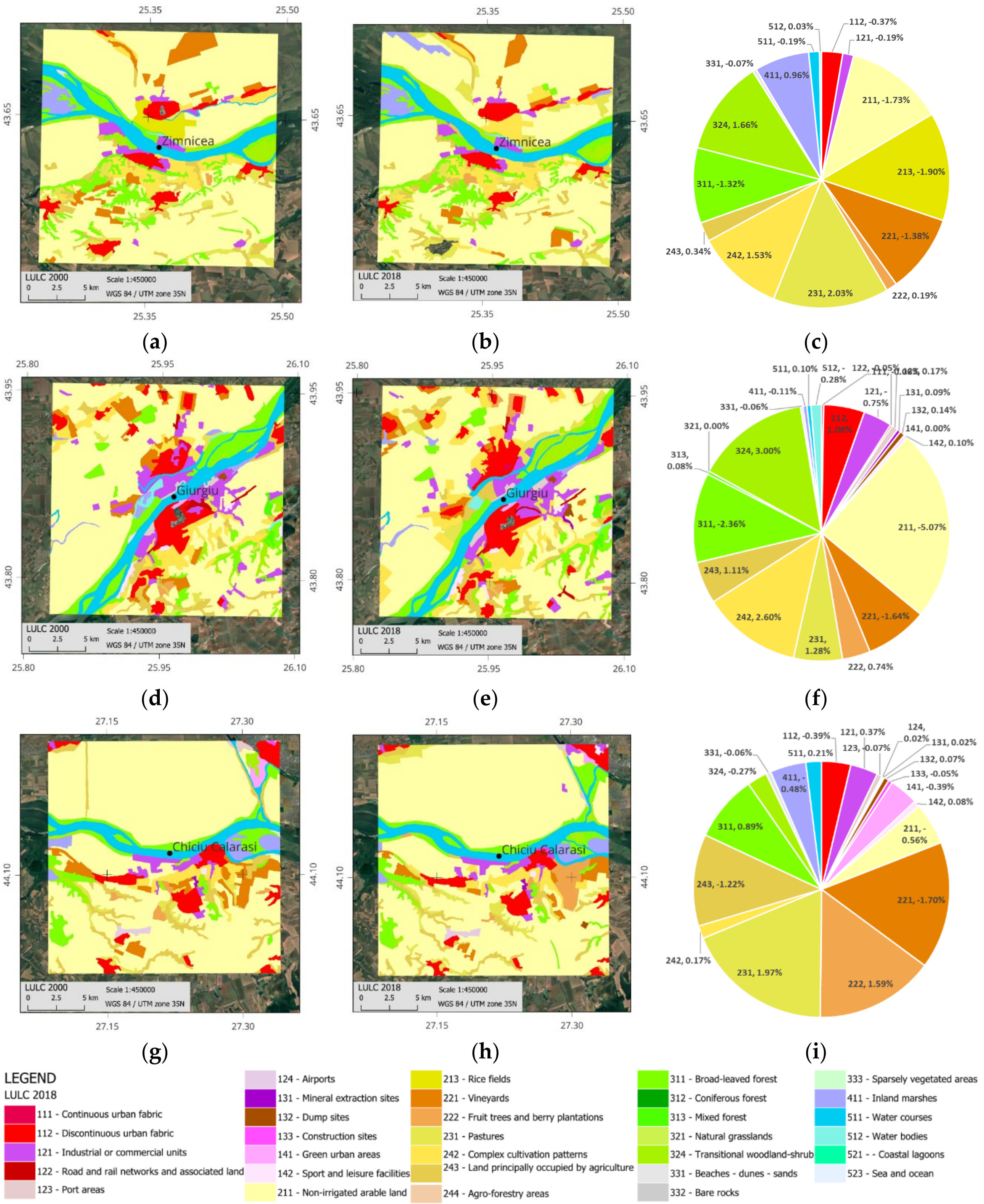

Figure 7. Geospatial and temporal changes of LU-LC 2000 (**a, d, g**) vs. LU-LC 2018 (**b, e, h**) at the Zimnicea, Giurgiu, and Chiciu–Călărași observation areas. The pie charts represent the percentage changes between the years 2000 and 2018 (**c, f, i**).

Between 2000 and 2018, the **Chiciu–Călărași** observation area (Figure 7g) recorded land-use modifications primarily within agricultural and natural classes. Pastures (221) decreased up to 718 ha, while fruit trees and berry plantations (222) and natural grasslands (321) expanded (+671 ha and +831 ha), indicating agricultural restructuring toward more diversified and perennial uses (Figure 7h). Land principally occupied by agriculture with natural vegetation (243) also diminished (–518 ha), suggesting consolidation or conversion to more intensive land use. In contrast, broad-leaved forest (311) increased by approximately 375 ha, pointing to localized forest recovery or afforestation. Moderate losses in inland marshes (411) (–202 ha) and gains in watercourses (511) (+88 ha) reflect

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adjustments in floodplain and hydrological conditions, with implications for sediment dynamics and bank stability along the Danube (Figure 7i).

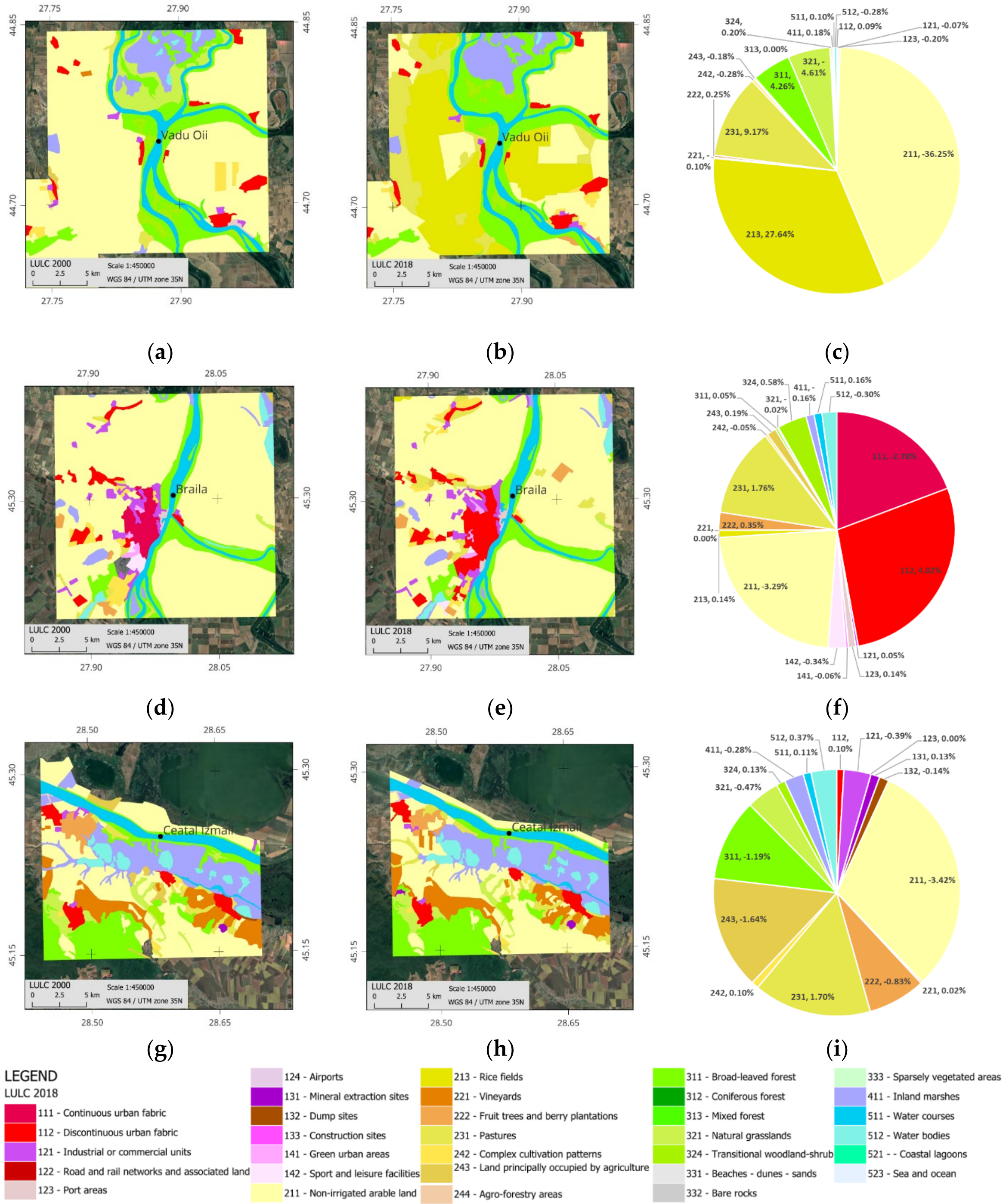

Figure 8. Geospatial and temporal changes of LU-LC 2000 (**a, d, g**) vs LU-LC 2018 (**b, e, h**) at the Vadu Oii, Braila, and Ceatal Izmail observation area. The piecharts represents the percentage difference of changes between years 2000 and 2018 (**c, f, i**).

Between 2000 and 2018, the **Vadu Oii** analysed area experienced pronounced land-use changes, influences by a major reconfiguration of agricultural and natural vegetation classes (Figure 8a,b). Non-irrigated arable land (211) decreased greatly by more than 15,100 ha (−36.25%), representing the most significant transformation in the area. This loss was generally offset by the evolution and expansion of rice fields (213) (+11,537 ha) and a increase in pastures (231) (+3,829 ha), indicating a fundamental modification in agricultural practices toward irrigated and grass-based systems (Figure 8c). At the same time, broad-leaved forests (311) increase substantially (+1,779 ha), while natural grasslands (321) declined significantly (−1,922 ha), suggesting vegetation succession and partial restoking of forests.

Between 2000 and 2018, the **Brăila** area indicates changes increase in discontinuous urban fabric (112), which expanded by approximately 1,666 ha (+4.02%), alongside the complete loss of continuous urban fabric (111), indicating urban expansion and spatial reconfiguration of built-up areas (Figure 8d). Agricultural land described by non-irrigated arable land (211) decreased by more than 1,360 ha (−3.29%) (Figure 8e), while pastures (231) and fruit trees and berry plantations (222) expanded up to 731 ha and 145 ha, respectively, reflecting diversification of agricultural practices (Figure 8f).

The upstream **Ceatal Izmail (Isaccea)** area shows coherent land-use changes dominated by agricultural matching (Figure 8g,h). Non-irrigated arable land (211) decreased by nearly 1,000 ha, while pastures (231) extended up to +481 ha, indicating a less intensive agricultural use. A strong reduction in land principally occupied by agriculture with natural vegetation (243) (−462 ha) suggests consolidation of land management or conversion to other uses (Figure 8i), due to the fact that this land is located in protected areas of the Danube Delta [36]. Slight increases in water bodies (512) and water courses (511) indicate localized hydrological adjustments within the Danube floodplain, with potential implications for sediment redistribution and bank stability in the Isaccea sector.

In comparison with the upstream Ceatal Izmail (Isaccea) area, the **Periprava sector** pick out a different LU-LC evolution, dominated by wetland and coastal dynamics rather than agricultural restructuring. Periprava shows losses in inland marshes (411) (−987 ha), natural grasslands (321) (−1,223 ha), and water bodies (512) (−789 ha), indicating floodplain contraction and hydrological reorganization (Figure 9a,b). In contrast, beaches, dunes, and sands (331) increase (+1,068 ha), highlighting active sediment deposition and coastal–deltaic processes specific to the Danube Delta environment (Figure 9c).

Between 2000 and 2018, the **Sulina** analysed area shows land-use changes strongly influenced by hydrological and coastal processes (Figure 9d,e). The most active change is the pronounced decline of inland marshes (411) by approximately 1,562 ha (−4.43%), indicating wetland reduction and altered floodplain dynamics. Non-irrigated arable land (211) also decreased (−448 ha; −1.27%), reflecting reduced agricultural presence. In contrast, recreational areas and facilities (142) expanded markedly (+469 ha; +1.33%), while beaches, dunes, and sands (331) increased by over 210 ha (+0.60%), emphasizing coastal sediment supply (Figure 9f). Moderate losses in watercourses (511) and gains in water bodies (512) suggest localized reconfiguration of aquatic surfaces. Overall, Sulina's LU-LC evolution is primarily driven by deltaic morphodynamics and wetland transformation rather than agricultural intensification.

Compared with Sulina and Periprava, the **Sfântu Gheorghe** area displays a more balanced LU-LC evolution, characterized by vegetation succession and relative hydrological stability rather than strong wetland loss (Figure 9g,h). The most significant change is the expansion of transitional woodland–shrub (324) (+721 ha; +1.73%), contrasting with the wetland reduction observed in Sulina and Periprava. Natural grasslands (321) and broad-leaved forests (311) decreased by up to −489 ha and −162 ha, while beaches, dunes, and sands (331) expanded (+262 ha), confirming ongoing delta-front sediment dynamics in the Periprava area (Figure 9i). Unlike Sulina, inland marshes (411) increased a bit (+255 ha), suggesting better floodplain retention. Overall, Sfântu Gheorghe represents an intermediate deltaic trajectory, where sediment accumulation and vegetation transition partially restore habitat losses seen in the eastern delta sectors [37].

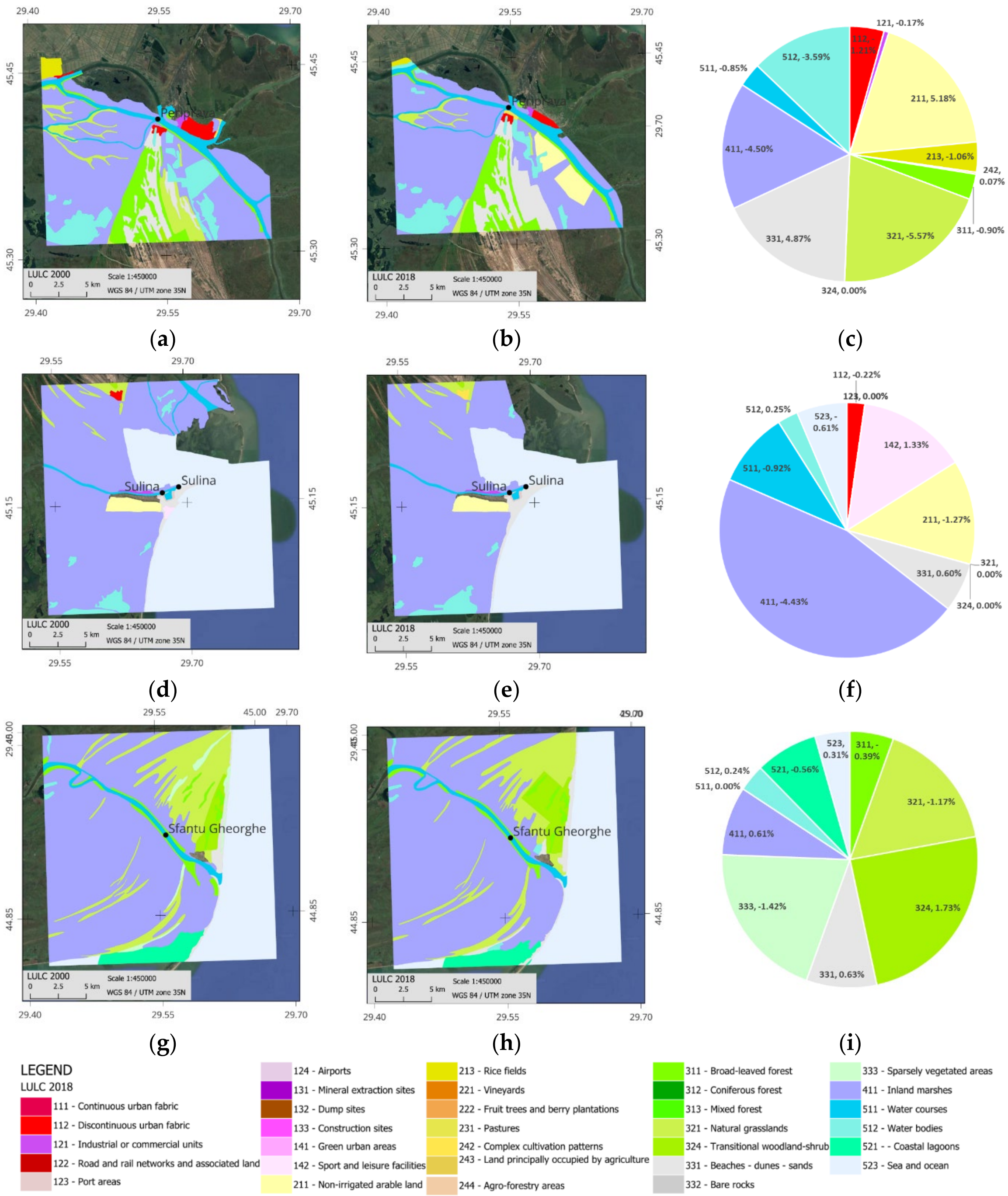

Figure 9. Geospatial and temporal changes of LU-LC 2000 (**a, d, g**) vs. LU-LC 2018 (**b, e, h**) at the Periprava, Sulina, and Sfantu Gheorghe observation areas. The pie charts represent the percentage changes between the years 2000 and 2018 (**c, f, i**).

At the **Zavala** observation point (Figure 10a,b), located on the Jiu River (a Danube tributary), land-use and land-cover changes between 2000 and 2018 were influenced by agricultural expansion coupled with floodplain wetland loss. Non-irrigated arable land (211) increased by more than 4,450 ha (+10.5%), representing the most significant transformation in the area. This expansion was coupled with a pronounced growth of rice fields (213) (+1,494 ha; +3.52%), indicating intensified and more water-dependent agricultural practices. In contrast, pastures (231) and land principally occupied by agriculture with natural vegetation (243) decreased(−2,636 ha and −892 ha), suggesting modification toward intensive cultivation (Figure 10c).

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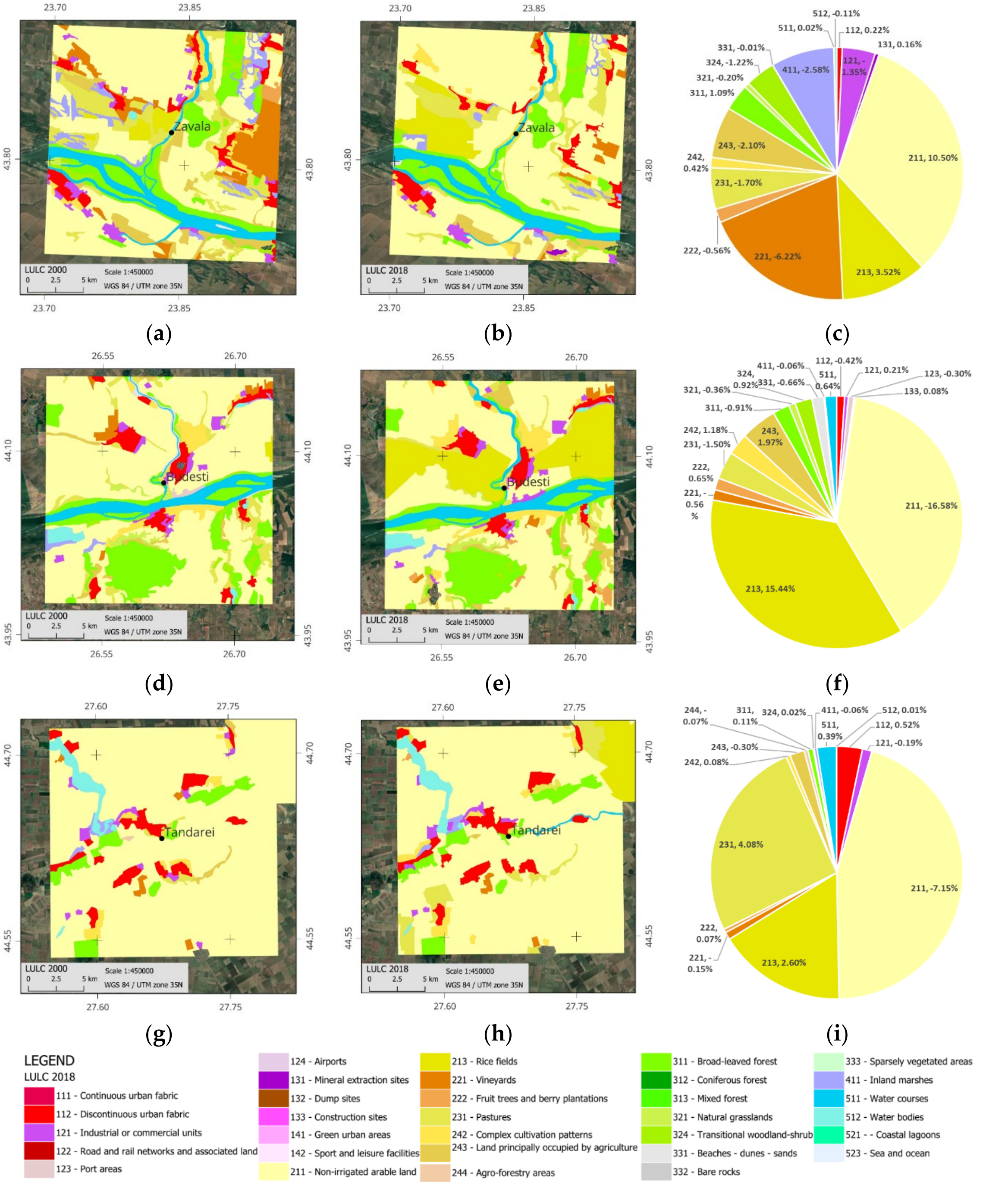

Figure 10. Geospatial and temporal changes of LU-LC 2000 (**a, d, g**) vs. LU-LC 2018 (**b, e, h**) at the Zavala, Budesti, and Tandarei observation areas. The pie charts represent the percentage changes between years 2000 and 2018 (**c, f, i**).

In the **Budești observation point**, located on the Argeș River, a major Danube tributary, land-use changes between 2000 and 2018 were the most pronounced modifications is the decrease of non-irrigated arable land (211) by nearly 7,000 ha (−16.6%), largely compensated by a strong expansion of rice fields (213) (+6,513 ha; +15.4%) and increases in complex cultivation patterns (242) and land principally occupied by agriculture with natural vegetation (243) (Figure 10f). These changes indicate a transition toward more water-dependent and fragmented agricultural landscapes. From a geomorphological perspective, the intensification of irrigated agriculture and the reduction of permanent grasslands increase the likelihood of enhanced surface runoff and fine-sediment mobilization during high-flow events. As the Argeș River directly discharges into the Danube, these

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LU-LC changes may contribute to increased sediment loads, influencing channel morphology, turbidity, and sediment deposition in the downstream Danube sector (Figure 10 d,e).

Figure 10g,h, more exactly at the **Țăndărei observation area**, located on the Ialomița River, indicates that the land-use changes between 2000 and 2018 were characterized by agricultural modifications with clear implications for sediment delivery to the Danube. Non-irrigated arable land (211) decreased by nearly 3,000 ha (−7.15%), while pastures (231) expanded strongly (+1,708 ha; +4.08%) from one period to the next, indicating a change of less intensive land use (Figure 10i). Minor increases in broad-leaved forest (311) and transitional woodland–shrub (324) provide limited compensation for the reduction of permanent agricultural vegetation.

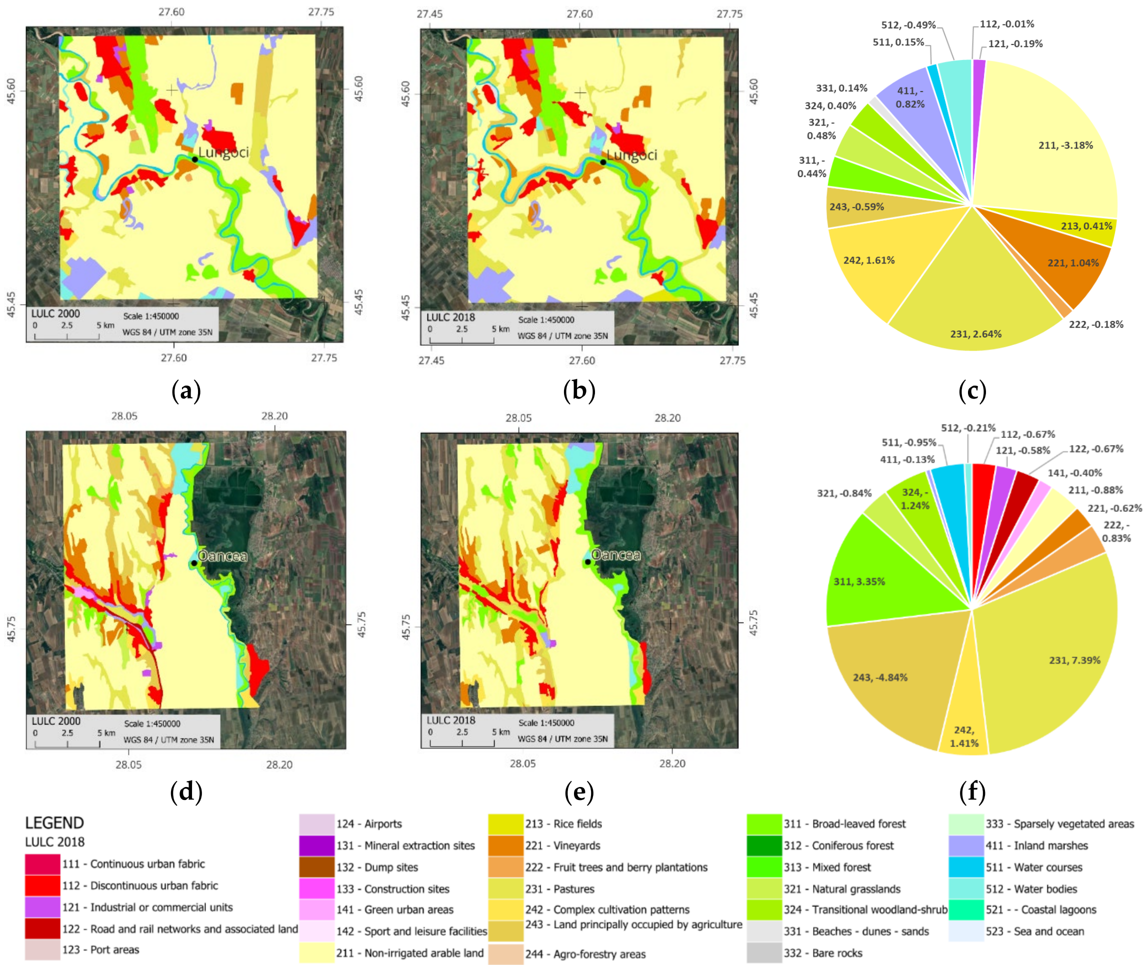


Figure 11. Geospatial and temporal changes of LU-LC 2000 (**a, d**) vs. LU-LC 2018 (**b, e**) at the Lungoci and Oancea observation areas. The pie charts represent the percentage changes between the years 2000 and 2018 (**c, f**).

In the Lungoci area, situated on the Siret River, one of the main tributaries of the Danube, land-use and land-cover changes indicates that the non-irrigated arable land (211) decreased by about 1,313 ha (Figure 11a), while pastures (231) and pastures/natural grasslands (231) expanded significantly (+429 ha and +1,088 ha, respectively) (Figure 11b). A high increase in complex cultivation patterns (242) (+665 ha) further suggests agricultural diversification. At the same time, land principally occupied by natural vegetation (243) and broad-leaved forests (311) decreased, pointing to a reduction in semi-natural buffer zones. Inland marshes (411) also decreased (−340 ha), reflecting floodplain reduction (Figure 11c).

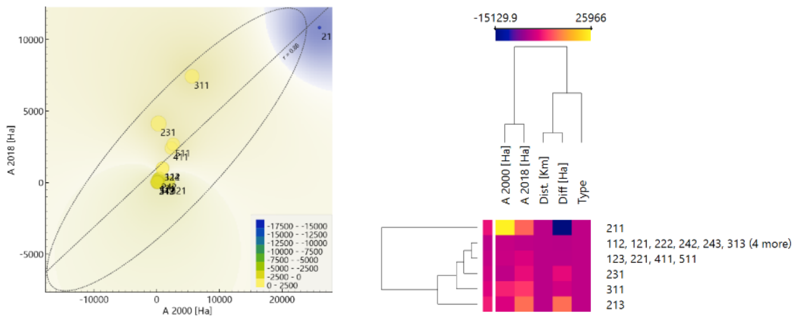
In the Prut River observation area (Oancea), land-use changes between 2000 and 2018 were characterized by a strong expansion of pastures (231) (+1,834 ha; +7.39%) and broad-leaved forests (311) (+831 ha; +3.35%), accompanied by a pronounced decline in land principally occupied by agriculture with natural vegetation (243) (−1,202 ha) and moderate losses in non-irrigated arable land

(211) (Figure 11d,e,f). This pattern suggests reduced agricultural intensity and increasing vegetation cover along the floodplain. Compared with the Lungoci area on the Siret River, where agricultural diversification dominates, and wetlands declined, the Prut sector is more strongly controlled by river sinuosity. The highly sinuous Prut promotes overbank flooding, lateral accretion, and local sediment trapping within meanders and floodplain forests, enhancing sediment deposition upstream. As a result, a larger proportion of sediments is stored locally, potentially reducing direct sediment transfer to the Danube. In contrast, the less sinuous Siret corridor allows more efficient sediment conveyance, contributing more directly to downstream Danube Sediment loads.

Statistics Perspective

The use of Pearson correlation was necessary to evaluate the degree of linear association between variations in land-class areas from 2000 to 2018. The value of the Pearson coefficient for all 17 locations ranged from +0.86 to +1.00, depending on the LU-LC change in each area. An example of the statistical analysis is shown in Figure 12a, illustrating a weak correlation between class areas. The statistical data of the Pearson correlation are presented in detail for each location in Figure S1.

At the same time, a K-means clustering with 6 clusters was also performed. Figure S2 presents in detail the statistical results of the clustering, optimized to six clusters, in which classes 112, 121, 222, 242, and 243 form a cluster with a dominant land type, but with varying dominance in each studied location. A strong clustering with these land classes is observed in the observation points Drobeta Turnu Severin, Vadu Oii, and Oancea. The rest of the observation points show a weak dominance of this cluster. In the statistical representations in Figure S2, in addition to the area of the terrain class and its type, the distance of the centroid of each class polygon to the riverbank (left or right) was also taken into account. This is an important parameter for identifying the influence of the proximity of different terrain classes on the banks (erosion, deposition, or instability) and to link the LU-LC changes in time to the areas with direct impact on the minor Danube River bed.



(**a**) (**b**)

Figure 12. Example of statistical analysis: (a) weak Pearson correlation for terrain-class type changes at the Vadu Oii observation point; (b) K-means clustering and strong domination between 2000 and 2018 at Vadu Oii observation point.

3.2. UAV Photogrammetry Validation Results

Unlike Sentinel-2 satellite images (10–20 m) (Figure 13a) or even Landsat (30 m), with the help of UAV flights, we managed to obtain a high-resolution orthophotomap. The resolution of the orthophoto map obtained was 0.05x0.05 m/px. To easier manipulate the orthophotomap this was resampled to 50x50 cm/pixel, a spatial resolution sufficient to delineate all types of LU-LC categories (Figure 13b).

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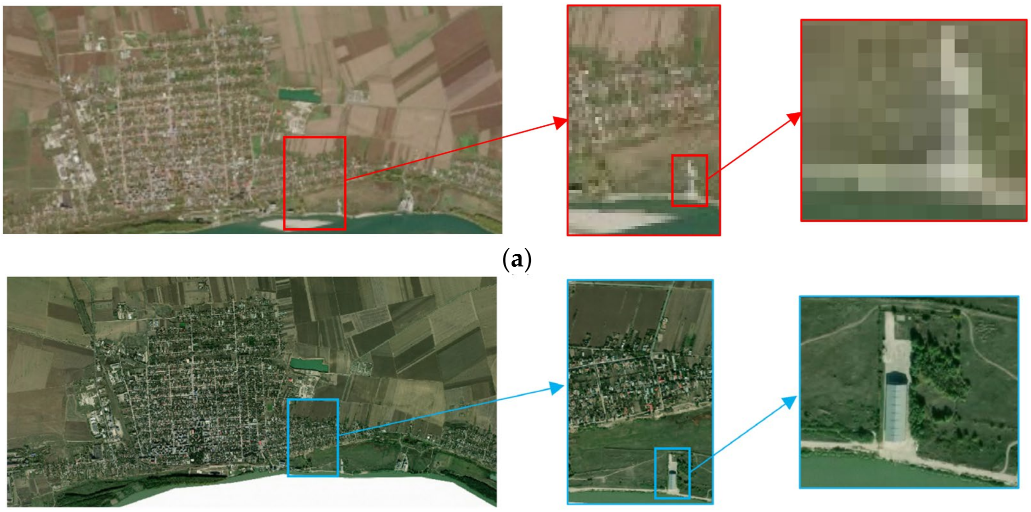

(**a**)

(**b**)

Figure 13. The resolution differences near the Corabia critical point: (**a**) Copernicus Sentinel-2 – 10x10m/pixel; (**b**) UAV ortophotomap – 0.5x0.5 m/pixel.

It allows the identification of fine details of the land surface, such as differentiating more accurate types of land, identifying spontaneous vegetation, detecting degraded surfaces, or analyzing the microstructures of the land that can influence geomorphological processes.

Field validation, performed by overlaying UAV images on LU-LC classifications from 2000 and 2018, allowed for the assessment of classification accuracy, detection of potential errors, and subsequent model adjustments.

For example, agricultural areas that represent the majority of the analyzed area have undergone significant changes over time, especially through land use transformations, such as transitions to pastures, fallow land, or spontaneous reforestation. Without validation with very high-resolution remote sensing techniques, many of these changes could remain unobserved.

The importance of accuracy in validation is directly correlated with the applicability of the results. LU-LC analyses are used in erosion risk assessment, sediment modeling, flood forecasting, land use planning, and decision-making regarding sustainable environmental management. Especially in areas close to large rivers, such as the Danube, the precision and accuracy of classification are essential to understand the dynamics of the banks. Bank erosion can be influenced by:

- type of vegetation and its density;
- extension of agricultural areas to the edge of the bank;
- loss of protective vegetation cover;
- Sometimes changes in microrelief may occur;
- sedimentation processes determined by hydrological flow.

Figure 14 presents the results of the land cover obtained in the Corabia hotspot area. Figure 14a represents the LU-LC coverage area from Copernicus in 2000. Figure 14b represents the LU-LC coverage area from Copernicus in 2018. Figure 14c,d represents the LU-LC coverage area obtained from UAV flights, orthophotomap result with a resolution of 0.50 x 0.50 m/px. The LU-LC obtained based on the UAV orthophoto was made by manual digitization. In remote sensing and GIS, raster images (UAV, satellite, aerial photographs) are made up of pixels, each pixel having a spectral value or color. These data, although very useful for analysis, are not directly interpretable as distinct geographic entities. Through vectorization, homogeneous areas or objects of interest (for example: agricultural plots, urbanized areas, water surfaces, edges, roads, riparian vegetation, etc.) are converted into precise vector shapes, with clear boundaries and associated attributes. Thus, manual digitization is a time-consuming but very precise GIS technique. The high-resolution orthophoto map is analyzed manually and the expert who digitizes it decides which land category is delimited by a

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shape. Thus, through a double combination of field validation and UAV flight, high-quality results were obtained regarding the updated LU-LC coverage.

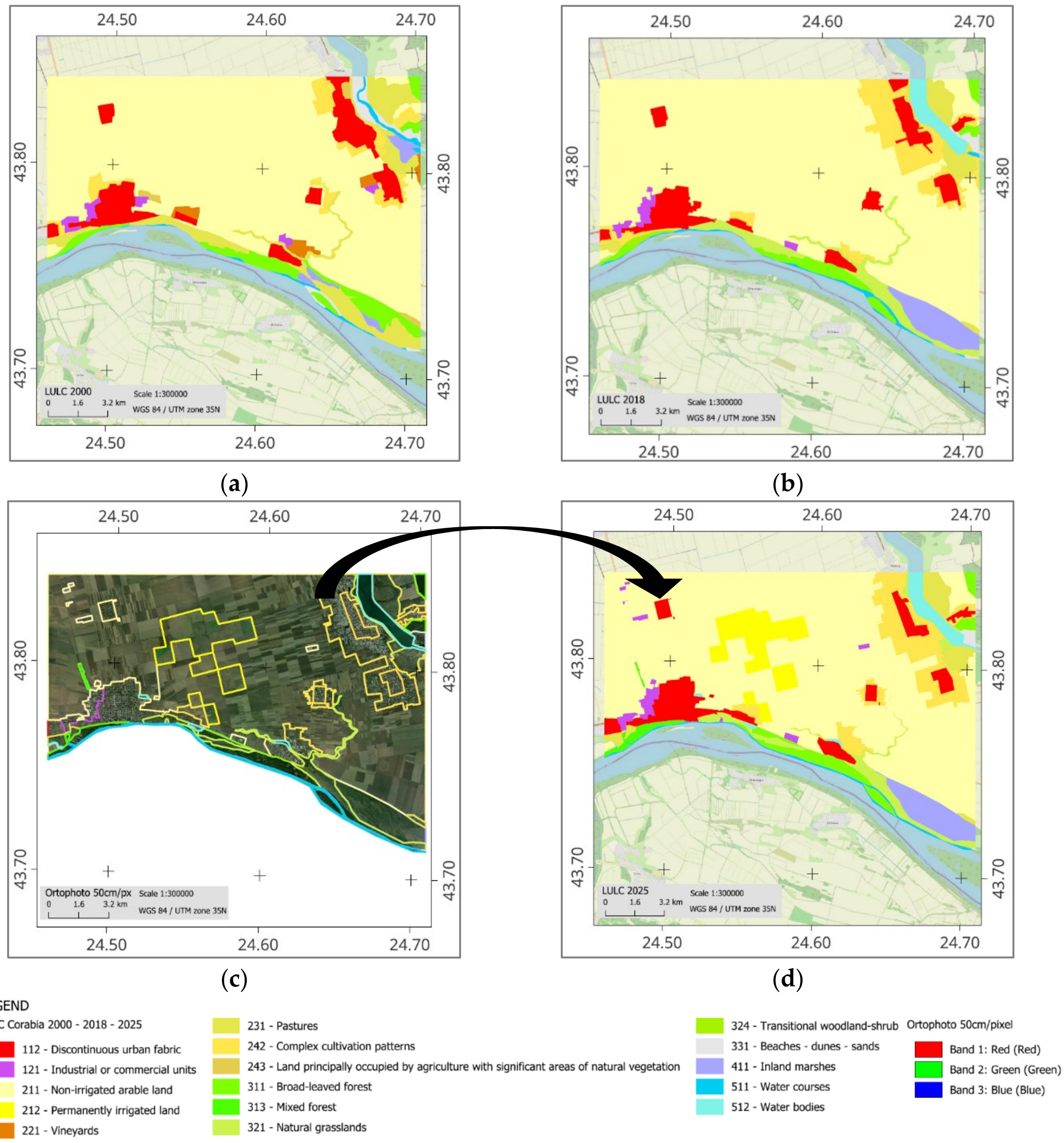
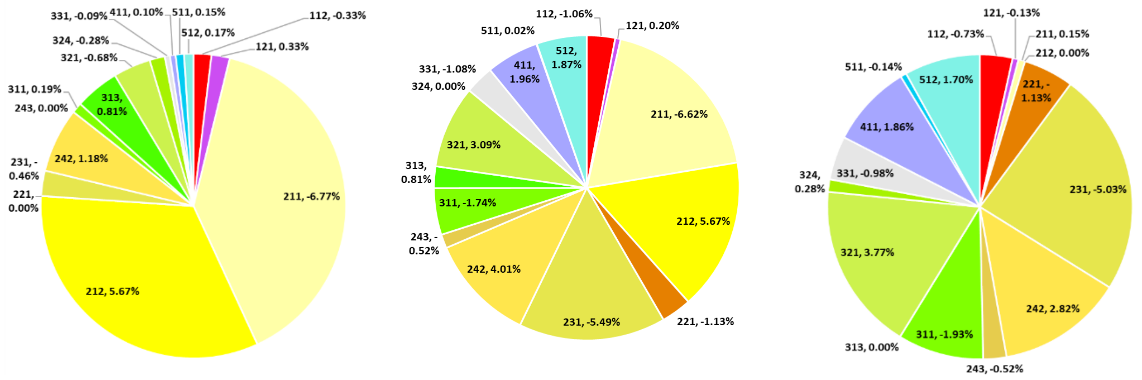


Figure 14. Comparative LU-LC maps for 2000, 2018, and 2025 with orthophoto-based boundary verification at the Corabia validation area: (**a**) – LU-LC of the year 2000; (**b**) – LU-LC of the year 2018; (**c**) – high resolution orthophotomap of the year 2025, 0.5 x 0.5 m/px, manually digitized LU-LC boundaries; (**d**) – LU-LC of the year 2025 obtained from UAV orthophotomap;.

By directly comparing UAV images (2025) with Copernicus classifications (2000 – 2018), differences such as the expansion or reduction of cultivated areas, the appearance of uncultivated areas, and changes in erosion and sedimentation paths were identified.



(**a**) (**b**) (**c**)

Figure 15. Temporal area differences of LU-LC related to high-resolution orthophoto map: (**a**) LU-LC 2025 vs. 2018; (**b**) LU-LC 2025 vs. 2000; (**c**) LU-LC 2018 vs. 2000.

Figure 15 presents a comparative numerical assessment of temporal LU-LC area differences, expressed as proportional changes (%) among distinct LU-LC categories across three temporal comparisons: (a) LU-LC 2025 vs. LU-LC 2018, (b) LU-LC 2025 vs. LU-LC 2000, and (c) LU-LC 2018 vs. LU-LC 2000. Each pie chart quantifies the relative gain or loss within standardized LU-LC classes, allowing for direct comparison of landscape transformations over nearly three decades.

Across all three panels, the most evident trends involve fluctuations within major agricultural categories (e.g., codes 211, 212, 221, 231, 242, 243). The total area ~~of the area~~ remains constant (21,218.12 ha), but the internal distribution of categories varies significantly. Several major trends are clearly distinguishable. Urban areas in class *112 – Discontinuous urban fabric* show a slow decrease, from 1,566 ha in 2000 to 1,342 ha in 2025 (Figure 14b), a difference equivalent to –1.06%. This reduction, although modest, indicates a process of local reconversion to agricultural, natural, or industrial land. Industrial class *121 – Industrial or commercial units* shows an oscillating evolution: decrease until 2018, then increase considerably until 2025 (+0.33% compared to 2018), which may reflect the relocation of economic activities or the development of new facilities (Figure 14a,b,c).

The most significant change, however, is observed in the structure of arable land. *Class 211 – Non-irrigated arable land*, dominant in 2000 and 2018, decreases significantly after 2018, reaching 13,551 ha in 2025, recording a total loss of –6.62%. This reduction of over 1,400 ha marks a weighty restructuring of traditional agriculture, either through abandonment or through functional conversion. In parallel, *class 212 – Permanently irrigated land*, absent in 2000 and 2018, appears in 2025 with an area of 1,203 ha, equivalent to +5.67% of the total. This massive appearance suggests investments in irrigation infrastructure, response to climate variability, and a transition towards intensive agriculture. Vineyards (221) were completely eliminated in 2018 and remain absent in 2025, indicating a loss of –1.13% of the area. Similarly, pastures (231) are reduced by over 5%, reflecting the decline of livestock activities and the conversion of land to other uses. In contrast, class *242 – Complex cultivation patterns*, associated with mixed agriculture and complex parceling, increases strongly (+4.01%), indicating diversification and adaptation to land fragmentation. Natural vegetation records a significant dynamic: Class *321 – Natural grasslands* goes from 800 ha in 2018 to 0 ha in 2000, then 655 ha in 2025, signaling ecological regeneration phenomena, probably as a result of agricultural abandonment or hydrological influence. Classes such as 313 – Mixed forest and 324 – Transitional woodland-shrub appear temporarily between 2018 and 2025, suggesting active processes of plant succession.

The results of area values of LU-LC from the years 2000, 2018, and 2025 are presented in Table 1. In the same table, the differences between this years are shown, related to the entire 21,218.12 ha area obtained from UAV surveys. In terms of hydromorphology, the clear expansion of wetlands is one of the most evident signals of change: 411 – Inland marshes grow from 231 ha in 2000 to over 647 ha in 2025 (+1.96%), and 512 – Water bodies appear in 2018 (360 ha) and grow to almost 397 ha in 2025 (+1.87%) (Table 10b). These transformations indicate an increase in hydrological connectivity, a potential rise in the underground water table, and the formation of aquatic micro-depressions. The fluvial classes 511 – Water courses and geomorphological and 331 – beaches, dunes, sands undergo minor changes, but the reduction of sandy areas (–1.08%) suggests a movement of sediments.

Table 1. Numerical area differences of LU-LC related to the entire analysed surface from high resolution orthophotomap.

(0) Terrain Type*	(1) Area 2000 [Ha]	(2) Area 2018 [Ha]	(3) Area 2025 [Ha]	(3) - (1) Value [%]	(3) - (2) Value [%]	(2) - (1) Value [%]
112	1566.15	1411.41	1342.05	-1.06%	-0.33%	-0.73%
121	210.60	182.51	253.26	0.20%	0.33%	-0.13%
211	14955.46	14987.47	13551.44	-6.62%	-6.77%	0.15%
212	0.00	0.00	1203.63	5.67%	5.67%	0.00%
221	239.07	0.00	0.00	-1.13%	0.00%	-1.13%
231	1715.00	648.11	550.06	-5.49%	-0.46%	-5.03%
242	776.71	1376.10	1626.73	4.01%	1.18%	2.82%
243	110.05	0.00	0.00	-0.52%	0.00%	-0.52%
311	948.14	538.66	578.71	-1.74%	0.19%	-1.93%
313	0.00	0.00	172.01	0.81%	0.81%	0.00%
321	0.00	799.97	655.13	3.09%	-0.68%	3.77%
324	0.00	59.30	0.00	0.00%	-0.28%	0.28%
331	282.73	74.35	54.48	-1.08%	-0.09%	-0.98%
411	231.18	625.56	647.46	1.96%	0.10%	1.86%
511	183.03	154.05	186.51	0.02%	0.15%	-0.14%
512	0.00	360.64	396.67	1.87%	0.17%	1.70%
Total	21218.12	21218.12	21218.12			

** 112 - Discontinuous urban fabric, 121 - Industrial or commercial units, 211 - Non-irrigated arable land, 212 - Permanently irrigated land, 221 – Vineyards, 231 – Pastures, 242 - Complex cultivation patterns, 243 - Land principally occupied by agriculture with significant areas of natural vegetation, 311 - Broad-leaved forest, 313 - Mixed forest, 321 - Natural grasslands, 324 - Transitional woodland-shrub, 331 - Beaches - dunes – sands, 411 - Inland marshes, 511 - Watercourses, 512 - Water bodies.*

Taken together, these changes indicate a transition from a predominantly extensive agricultural system to a mixed landscape, characterized by irrigated agriculture, natural vegetation regeneration, and the expansion of wetlands.

These changes in LU-LC at the Corabia observation point, resulting from UAV field validation, directly or indirectly influence erosion and sedimentation processes: the reduction of non-irrigated arable land increases wind erosion, mobilizing fine particles toward the Danube banks during drought; alluvial erosion from land to the Danube; and the expansion of marshes and lakes in the vicinity of the banks improves sediment retention but decreases water-flow velocity when the water level is high. This information plays a crucial role in assessing the stability of the banks and the erosion risk, since vegetation and soil structure significantly influence the hydrodynamic behavior. Areas without vegetation or with exposed land are more susceptible to accelerated erosion during increased Danube flows, which leads to increased sediment transport and modification of its distribution downstream.

Overall, the hydromorphological regime of the area has become wetter and more complex since 2000, reflecting an ongoing ecological and agricultural reorganization.

Visible Bank Erosion Results

The impact of LU-LC on the stability of riverbanks (Corabia sector, Danube) is an important indicator for the geomorphological analysis of an area.

In the Corabia sector, the Danube River has complex hydrological and sedimentary dynamics, influenced by flow variations, the exploitation regime of upstream hydrotechnical developments, and anthropogenic and natural interventions on the banks. In this river sector, more precisely Corabia-Turnu Magurele, the area where UAV flights were also carried out for the comparative analysis of LU-LC, active erosion occurs, which over time leads to significant losses of land related to bank protection infrastructure. In caertain cases, there is also the possibility of losses of arable land or of land classified as protected natural areas. These land losses due to erosion or sediment deposition in the bank area can directly affect river navigation and may also influence riparian habitats.

If we also refer to the connection with the determinations regarding the LU-LC changes in the Corabia area (comparative analysis 2008-2025), these play a direct role in the erosion and deposition processes in the riverbank area. The conversion of natural or semi-natural surfaces into arable land, regardless of type (non-irrigated arable land, intensive crops, compact plots), leads to the reduction in vegetation that has a stabilizing role on the banks.

Thus, to identify the effect of erosion or sedimentation in the area of the banks of a river, the changes that occurred in different periods of time were analyzed using GIS techniques - an aspect identified and analyzed also in the same area of interest - Corabia - Turnu Magurele (Figure 16).

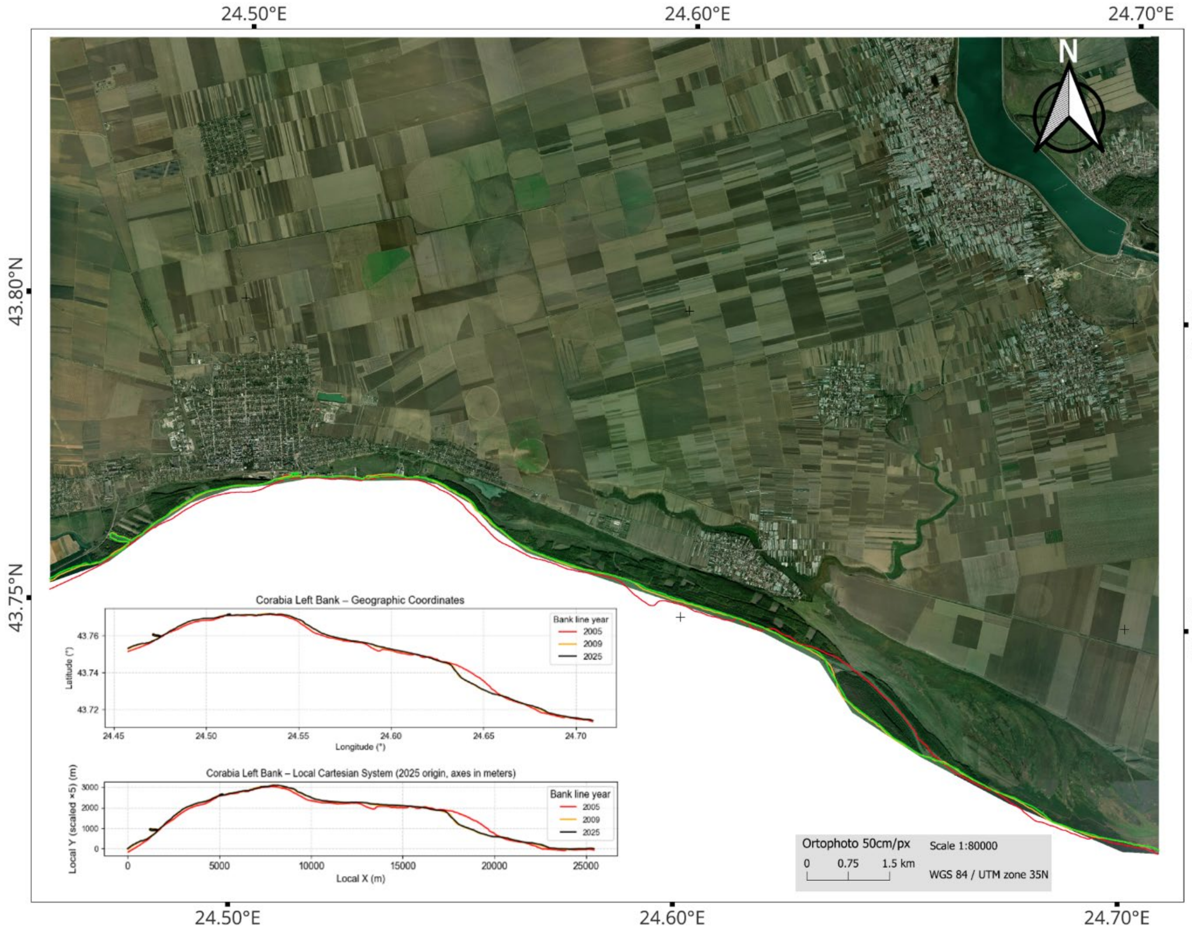
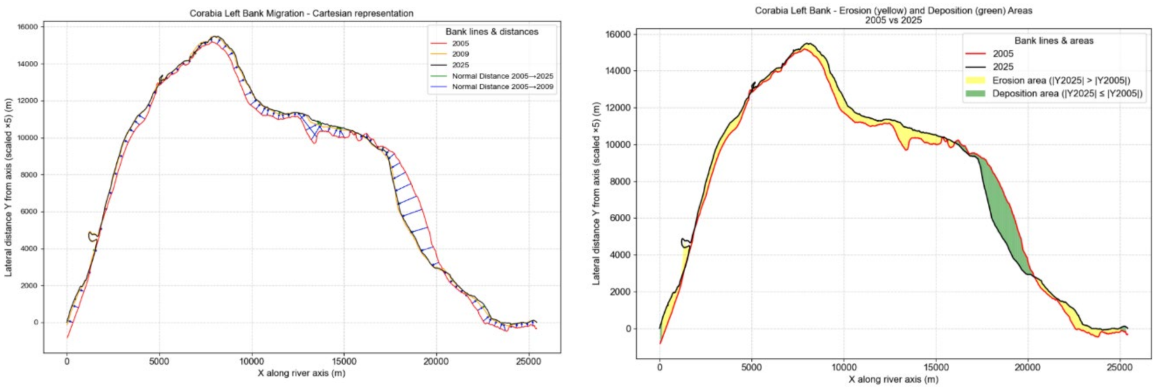


Figure 16. Multitemporal dynamics of the left bank line of the Danube in the Corabia sector (2005–2009-2025).

The shoreline dynamics analysis method is based on comparing shoreline positions for the years 2005, 2009, and 2025, using a local Cartesian coordinate system derived from the reprojection of data from UTM 35N (Figure 17a). The shorelines for 2005 and 2009 were extracted by manual digitization of satellite images from the historical Google Earth Pro archive, and the 2025 shoreline was extracted from orthorectified UAV data. The comparison of banklines was made exclusively between 2005 and 2025, because the preliminary analysis showed that no significant changes in the banklines occurred in the period 2009–2025. The data from historical images were chosen to have the same water-level, to eliminate the possibility of water-level distortion and input errors. To ensure geometric consistency, the 2025 line was used as a reference, translated so that the initial point coincided with the origin of the Cartesian system (0,0), and the general direction of the bank was aligned with the X-axis. The 2005 lines were subjected to the same transformation (translation and rotation), allowing direct comparison of deviations along the Y axis. The graphic representation of the banks in Cartesian coordinates facilitates the identification of erosion and deposition areas and allows the quantification of spatial changes of the bank along the entire analysed length (Figure 17b).



(**a**) (**b**)

Figure 17. Cartesian representation of banklines: (**a**) distances from the 2005 reference line to 2009 and 2025 years; (**b**) erosion and deposition areas 2005 vs 2025.

If we analyse the digitized data, we can confirm that clear and spatially consistent changes in riverbank position are evident between 2005 and 2025 (Figure 17b). The comparison highlights a pronounced imbalance between depositional and erosional processes along the left bank. The total deposition area identified for these two periods is approximately 101.7 ha. Conversely, the erosion area is significantly larger, amounting to about 158.7 ha, reflecting dominant bank retreat processes. This asymmetry suggests an overall negative sediment balance for the analysed sector, with direct implications for land loss, bank stability, and long-term river morphology. In the Corabia sector, the influence of LU-LC changes on bank erosion is minimal because the relief is predominantly flat, with slightly pronounced slopes. However, the extension of arable land to the Danube riparian area poses a risk by reducing protective vegetation and increasing bank erosion. In order to slow down the erosion effect and sediment transport from the bank to the Danube river channel, it is first necessary to maintain or restore riparian vegetation by applying solutions, such as Nature Based Solution (NBS).

Regarding the sediment deposits around the bank, which were created over time from 2005 to the present, in the area of the Corabia critical point, they also have a positive effect. The positive effects include the creation of new habitats and the strengthening of the banks. On the other hand, negative effects may occur when flows decrease, or certain areas become clogged (entrances to channels or the appearance of isolated islands), thus reducing sediment transport capacity and affecting the navigable channel.

The presented approach, which concerns the comparison of the erosion/deposition effect in the bank area, applied specifically and very precisely in the critical area of Corabia, can be used as a model and applied in other critical sectors. The comparative analysis performed helps to identify common erosion and deposition patterns, supporting the planning of river management measures and the prevention of land loss.

5. Conclusions

In conclusion, the detailed analysis of 20x20 km areas at each observation point along the Lower Danube sector, from the upstream entrance of the Danube at Baziaș to the downstream deltaic sectors and the main tributaries, reveals well-defined geospatial changes.

Thus, in the upstream and middle areas of the Danube (Baziaș, Drobeta–Turnu Severin, Corabia, Zimnicea, Giurgiu, Chiciu–Călărași), LU-LC changes are dominated by changes in agricultural destination and urban development. The consolidation of large arable plots, the reduction of permanent crops, and the decline of pastures and semi-natural buffer zones reduce soil protection against erosion and thus increase the efficiency of runoff. In several sectors (e.g., Giurgiu, Zimnicea), the conversion of arable land to heterogeneous agriculture and transitional vegetation partially mitigates erosion, but forest loss and wetland shrinkage locally reduce sediment retention. Where floodplains are extensive but constrained in terms of single-bed size (e.g., downstream of the Iron Gates), sediments move more rapidly downstream when flows are high.

In the floodplains of the lower Danube and its tributary systems (Jiu, Argeș, Ialomița, Siret, Prut), agricultural intensification - especially the strong expansion of irrigated systems - significantly changes the influence on sediment movement. Irrigated agriculture and reduced grassland cover increase the mobilization of fine sediments through surface runoff and wind-driven processes. Tributaries with less sinuosity (e.g., Argeș, Siret) favor more rapid sediment movement to the Danube, whereas tributaries with increased sinuosity (Prut River) favor deposition on the banks, reducing transport to the Danube.

In the Danube Delta sectors (Periprava, Sulina, Sfântu Gheorghe), sediment dynamics are mainly controlled by deltaic morphodynamics, rather than by agriculture.

In conclusion, the different changes in the LU-LC of the localities of Periprava, Sulina, and Sfântu Gheorghe demonstrate how sediment dynamics describe different morphological forms in the Danube Deltaic-coastal area. In Periprava and Sulina, the decrease of wetlands and the expansion of beaches and sandy surfaces indicate a change in the lands covered with sediments originating from their transport, either from the main channel or from the connecting channels in the Danube Delta. This also increases the migration of the shoreline and the shrinkage of floodplains. In contrast, Sfântu Gheorghe maintains the size of the floodplains through the diversity of vegetation and stable marshes, favoring local sediment deposition. Together, these changes in LU-LC indicate that variations in sediment retention and their redistribution completely change the channel-floodplain configurations, controlling the rapid degradation of the Danube delta area, maintaining certain habitats of international interest in the long term.

On rivers where alluvium is very high, changes in agricultural land use affect the stability of the banks under certain conditions.

Therefore, alterations in riparian vegetation cover play a significant role in controlling soil resistance and riverbank stability, thereby influencing erosion rates. Research synthesized from satellite images and validated in situ and through numerical calculations in the Corabia–Turnu Măgurele sector, as well as analyses of information from other projects implemented in this field (DanubeSediment and SIMONA), indicate that agriculture is rarely the sole dominant factor in bank erosion; rather, it acts as a multiplier.

At the Corabia observation point, the quantified comparison between 2005 and 2025 shows substantial lateral changes of the banks, with an overall dominance of erosion (≈158.7 ha) over deposition (≈101.7 ha). This imbalance indicates strong lateral movement of the banks toward the main channel. It is important to note that the analysis also suggests that the changes between 2009 and 2025 were not major, implying that the most relevant displacement occurred earlier (2005–2009). In such a context, agriculture influences bank erosion less through basin-scale slope processes (since the relief is flat) and more through microtopography in the area adjacent to the banks. Where arable plots extend into the immediate riparian zone, removal or thinning of woody riparian vegetation reduces root cohesion and bank strength, increasing the likelihood of bank failures and step collapses.

LU-LC analysis at several critical points of the Lower Danube demonstrates that agricultural categories dominate floodplain landscapes and that structural changes occur over time: consolidation of arable plots, introduction or expansion of irrigated land, decline of permanent pastures/crops in some sectors, and partial regeneration of natural vegetation in others. These changes modify the potential for sediment availability and movement. Non-irrigated arable plots and intensively cultivated plots typically increase soil exposure and increase the mobilization of fine sand particles. Irrigated agriculture can further increase soil disturbance, alter moisture regimes, and create directional pathways for the flow of alluvium and suspended matter, increasing the movement of fine sediments and the transport of nutrients to the Danube River. In contrast, pastures, wetlands, and riparian forests tend to reduce this transport and help to increase the level of water infiltration into the soil, thus keeping fine particles that can move from the fields into the flow zone of the minor riverbed.

However, in a floodplain with similarities to those in the critical area of Corabia, the change in land use, especially agricultural land, has a secondary effect in terms of hydraulic parameters: migration of the thalweg towards the bank, increase in flow speed, or modification of the banks. The effect is rather cumulative with other hydro-meteorological factors: high flows, heavy rains, and flood hazard situations. Therefore, under certain conditions, there is also a direct effect: agriculture carried out in the area close to the banks or protective dikes results in faster erosion of the banks than in areas covered with vegetation or protective forest belts. Even if the basin slopes are small, the buffer near the bank remains critical, as it is the last protective layer that controls whether hydraulic shear translates into bank retreat.

In conclusion, the use of UAV techniques increases confidence in the analyses performed. Validating LU-LC satellite data with in-situ data obtained from UAV flights provides a detailed image of steep banks, drainage channels, areas with urban/agricultural expansion or diminution, etc.

Thus, high-resolution images help identify local hydromorphological characteristics, capturing not only general large-scale behavior but also micro-scale dynamics. In practice, the results obtained from the study in the Corabia area support their general applicability to any similar study area (fluvial): agricultural land influences bank erosion mainly by modifying the integrity of the Danube riverside buffer zone, long-term runoff near the bank and the cumulative interactions with the pressures from navigation intensification as well as the anthropogenic pressures generated by the hydrotechnical constructions along the Danube River. Hydromorphology thus changes over time and space.

Supplementary Materials: The following supporting information can be downloaded at: Preprints.org, Table S1. Reference points for Task 1.4 on the Romanian Sector; Figure S1. Statistical correlation of LU-LC Copernicus areas between year 2000 and 2018: (a) Bazias; (b) Drobeta Turnu Severin; (c) Corabia; (d) Zimnicea; (e) Giurgiu; (f) Chiciu Calarasi; (g) Vadu Oii; (h) Braila; (i) Ceatal Izmail; (j) Periprava; (k) Sulina; (l) Sfantu Gheorghe; (m) Zavala; (n) Budesti; (o) Tandarei; (p) Lungoci; (q) Oancea.; Figure S2. K-means clustering of the data for visualizing the strongest and weakest clustering (optimize to 6 clusters for terrain type): (a) Bazias; (b) Drobeta Turnu Severin; (c) Corabia; (d) Zimnicea; (e) Giurgiu; (f) Chiciu Calarasi; (g) Vadu Oii; (h) Braila; (i) Ceatal Izmail; (j) Periprava; (k) Sulina; (l) Sfantu Gheorghe; (m) Zavala; (n) Budesti; (o) Tandarei; (p) Lungoci; (q) Oancea

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Abbreviations

The following abbreviations are used in this manuscript:

LU-LC	Land Use – Land Cover
UAV	Unmanned Aerial Vehicle
PM_{10}	Particle Matter with a diameter of 10 micrometers
PM_{10}	Particle Matter with a diameter of 2.5 micrometers
CO	Carbon monoxide
NOx	Nitrogen Oxides
ICPDR	International Commission for the Protection of the Danube River
EU	European Union
SIMONA	Sediment-quality Information, Monitoring and Assessment System
UTM	Universal Transverse Mercator
GIS	Geographic Information System

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