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Multi-criteria evaluation for the sustainable use of loess gullies in rural–urban borderline

Jan Rodzik[1], Beata Żuraw[2], Barbara Sowińska-świerkosz[2]✉, Jakub Kuna[3], Małgorzata Sosnowska[4] & Marek Podsiedlik[5]

The paper explores the issue of sustainable use of urban gullies under the pressure of suburbanization. The objective of this study was to provide guidelines for land restoration in relation to the Polish case study by analyzing (1) land cover changes, (2) their impact on the geomorphic evolution of gullies and (3) valuable plant associations. To this end, GIS technologies, identification of soil and sediments and valorization of plant associations were adopted to capture the total set of impacts. The findings revealed that land cover change indicators combined with geomorphological and plant aspects are useful for assessing the state of gully development and, on this basis, for providing revitalization recommendations. Long-lasting anthropogenic modifications were the main driving factors of gully development and exhibited significant interrelationships among all the indicators. This study revealed the need for strengthening the recreational use of gullies through multifunctional use by different citizen groups and for simultaneous protection of gullies in terms of geological and ecological aspects. This direction of action enables gully development and use in accordance with the sustainable development concept, which focuses on equal economic growth that generates wealth for all without harming the environment.

Keywords Gully, Degradation, Management, Revitalization, Loess relief, GIS

Urban sprawl and intensive suburbanization result in the development absorption of surrounding rural areas and their intercorporation into cities. Residents who move to suburbs expect contact with nature and the natural landscape while having good access to the transport system and a wide range of social and cultural services. Such development, however, has caused ecological load and degradation of such still substantially natural areas. This leads to a number of problems with their management in terms of both preserving their natural features and meeting the needs of their residents[1]. An imbalance between natural and social systems has caused a multitude of environmental challenges, resulting in increasingly vulnerable ecological environments[2,3]. As a result, unique landforms, such as gullies and forms of greenery connected to them, are being degraded worldwide. For example, in relation to Southwest Nigeria, Adediji and Ibitoye[4] observed intensive urban degradation processes caused by the development of buildings and urban infrastructure as well as by littering. Similar problems were observed in the cities of Brazil[5]. In China, the gully development process and the scale of its devastation have been reported to be dependent on many factors related to both spatial characteristic and natural events[6]. For example, in the past, disastrous downpours caused muddy floods in gullies that, in some cases, led to complete devastation of urban infrastructure[7–10]. Although gullies are considered in some countries as attractive elements of landscape, e.g. Louchan Loess National Geopark in China[11], Loess Geopark in Vojvodina in Serbia[12,13], "The land of loess gullies" on the Nałęczów Plateau in Poland and the legally protected Queen Jadwiga gully in Sandomierz, Poland[14], their presence in the vicinity of buildings is currently threatened by rapid spatial development. As such more accurate and robust strategies and methods are needed for sustainable development and use of these unique geomorphological structures.

To analyze the degradation process and better protect these unique environmental structures, geographical information systems (GIS) and remote sensing data are currently used (e.g., Refs.[10,15–17]). For example, different indices, such as the normalized difference vegetation index (NDVI), soil organic matter content and canopy

[1]Institute of Earth and Environmental Sciences, Maria Curie-Skłodowska University in Lublin, Al. Kraśnicka 2D, 20-718 Lublin, Poland. [2]Department of Hydrobiology and Protection of Ecosystems, University of Life Sciences in Lublin, Dobrzańskiego 37, 20-262 Lublin, Poland. [3]Institute of Socio-Economic Geography and Spatial Management, Maria Curie-Skłodowska University in Lublin, Al. Kraśnicka 2D, 20-718 Lublin, Poland. [4]Department of Grassland and Landscape Planning, University of Life Sciences in Lublin, Akademicka 15, 20-950 Lublin, Poland. [5]Independent researcher, Poznan, Poland. ✉email: barbara.swierkosz@up.lublin.pl

cover ratio, are used to monitor erosion at large temporal scales. Additionally, geo-environmental variables such as land use configuration and geological and hydrological characteristics are commonly used[18,19]. Such analysis allows us to correlate the processes of gully development with both natural and anthropogenic parameters such as slope length, profile curvature, vegetation coverage and land use types[20]. In addition to standard methods, machine learning is also used to analyze gully degradation processes[21]. Nonetheless, the factors controlling urban gully expansion, particularly their interactions, are still poorly understood[10,22,23]. One factor contributing to this knowledge gap is the complex nature of gully development caused by both natural and anthropogenic factors. Therefore, it is difficult to collect data on this process[10]. Hence, to fully reconstruct the history of urban gully development, an interdisciplinary approach should be applied to capture all the types of factors and link geomorphological and plant surveys with social and cultural factors.

Considering the scale of degradation of the unique urban geomorphological structure and the related types of greenery, analysis of gully development should be the first stage. The next stage should be the formulation and introduction of appropriate protection and management actions to mitigate the negative impact of disturbances on these types of ecosystems. For example, ecological vulnerability assessment is the scientific method used to identify vulnerability and thus contributes to maintain ecological stability and promote environmental management[24,25]. Another example is multicriteria decision analysis, which helps to understand the impact of natural and anthropogenic variables with the aim of better protecting and managing adaptatively vulnerable ecosystems[26]. In the case of vast gully systems with natural and/or rural characteristics, such an assessment usually leads to ecological zoning based on climate, ecological and geomorphological indicators[2,27].

The situation is different for small gullies located within city limits. They suffer from strong human pressure and cannot be left as enclaves of natural, unorganized greenery[28–30]. A lack of control results in wild garbage dumps and places where animals live, these areas are undesirable in large cities. Sustainable development is particularly affected by social aspects, making management a challenging task. Such problems related to gullies within city boundaries are also serious in Lublin, a large city in East Poland. Cities developed particularly intensively in the second half of the twentieth century, when administrative boundaries were changed several times. Over a period of 35 years, the area of the city grew almost five times, from 30.1 to 147.5 km^2. The formerly areas on the plateau were gradually occupied by residential districts and roads. Dry valleys were usually allocated for recreational areas. Largely inaccessible small gullies, particularly those located in the suburbs, remained mostly undeveloped. An example of such a neglected area is the Lipniak loess gully, which is currently located at the western boundary of the Lublin area. Considering the current conditions and management problems of this area, the research question was how to sustainably develop this gully while simultaneously protecting its unique ecological values and making it accessible to the public. To answer this question, multiple criteria analyses were applied to determine its development history. The specific objectives of this study were to (1) determine the land use/cover changes in the vicinity of gullies, (2) assess their impact on the geomorphic evolution of gullies and (3) analyze valuable plant associations and, on this basis, to (4) provide guidelines, recovery measures and projects for the sustainable use of the analyzed gully. To do so, an interdisciplinary approach linking GIS technologies, identifying soil and sediments and evaluating plant values was adopted to capture the total set of impacts.

Materials and methods

Conditions for undertaking the research topic and study area description

The methodology was tested in relation to the case study of Lublin city, as Lublin is the only large city in Poland that is largely situated on a loess area. Lublin is located on the Lublin Upland, upon the river Bystrzyca, near the mouth of the tributaries Czerniejówka and Czechówka (Fig. 1A). The northwestern part of the city is located on the left bank of the river within the eastern boundary of the loess mesoregion, the Nałęczów Plateau. The thickness of the loess cover, originating particularly from the Weichselian glaciation, amounts to 10–20 m in Lublin[31]. The Loess Plateau is located at an altitude of 200–230 m a.s.l., 30–50 m above the floor of the Bystrzyca River. The Loess Plateau is enriched by dry erosion-denudation valleys with branches of trough hollows. The density of such valley landforms in Lublin amounts to approximately 2.5 $km \cdot km^{-2}$. The valley network developed in the late glacial period[32]. In the Holocene, the area was intruded by a forest: first, boreal and then typical broadleaf forest. Deep luvic soils developed under the forest[33]. The agricultural use of these plants provided conditions for linear and sheet erosion, causing transformations of dry valleys. Roads running along these valleys transformed into small gullies with widths of up to a dozen meters. The density of these gullies in Lublin does not exceed 0.2 $km \cdot km^{-2}$. The network of dry valleys consists of 87 distinct structures, located primarily in the northwestern and southern parts of the city[34]. Gullies present significant challenges in the spatial planning and urban land management of Lublin. As valuable natural features, they should be preserved while being shaped in a sustainable manner. Without proper management, they can become hazardous and neglected elements of the urban landscape. Additionally, they often serve as habitats for rats, foxes, feral dogs, and invasive plant species. Currently, 12 of these valleys are either fully or partially developed and integrated into the city's green infrastructure system. The developed areas generally consist of extensive dry valleys. Their development typically involves the creation of paved pedestrian and cycling paths (constructed from concrete or paving stones) at ground level, the establishment of rest areas with benches and shelters, playgrounds, as well as regular mowing of grassy surfaces and removal of underbrush. Smaller, less accessible ravines, particularly those located on the outskirts of the city, have largely remained undeveloped. None of Lublin's gullies have been fully developed in an ecologically friendly manner. They lack features such as above-ground walking paths or pedestrian-cycling trails, observation points for flora and fauna, or educational elements that would harmoniously integrate with and protect the natural and landscape values of these formations.

One of the longest gullies in Lublin is called Lipniak and is located in the Węglin district and flows into the Konopniczanka River valley (Fig. 1A, B). Four segments can be distinguished along the 800 m course, 3 of which are currently developed. The first one (I) of the SSE-NNW orientation is totally occupied by allotment gardens.

Fig. 1. (**A**) Relief of the Lublin area according to the digital elevation model (compiled by J. Kuna); (**B**) Lipniak gully area together with the investigated sections and cross-sections (compiled by J. Kuna); (**C**) the entrance to the gully from Lipniak Street (photo by B. Żuraw); (**D**) sequence of synanthropic plant (photo by B. Żuraw) (Compiled by J. Kuna & co-authors, using QGIS 3.16.7, CorelDRAW 2019 & Adobe Photoshop CS6 software).

The second one (II) is of the SSW-NNE orientation and is still not developed (Fig. 1C, D). The third one (III), which is on the SSW-NNE orientation, has several lateral landforms, paved entrances to the property and an asphalt road (Lipniak Street), characterized by slopes occupied by clusters of linden trees (Fig. 2E). Similarly, the fourth outlet section (IV) has a SE–NW orientation and slopes developed with landscaped greenery (Fig. 2F).

Fig. 2. (**A**) Mid part of the gully (photo by B. Żuraw); (**B**) a littered part of the gully (photo by B. Żuraw); (**C**) inhabited red fox burrow (photo by B. Żuraw); (**D**) hard shield-fern (photo by B. Żuraw); (**E**) asphalt road and slopes with old trees (photo by B. Żuraw); (**F**) landscaped greenery (photo by B. Żuraw) (Compiled by J. Kuna & co-authors).

In this study we assess the undeveloped section (II), which included neglected and littered segments of gully and is indicated in local plans for development as a pedestrian and bicycle path (Fig. 2A, B). Its geographical coordinates are 51° 14′ 11″ N and 22° 29′ 03″ E. This segment is barred from the side of Lipniak Street with a debris-soil embankment. To the right, it borders on allotments gardens. The floor and slopes of the gully are overgrown by dense tree and shrub vegetation to the left, fallow fields slope down to the gully, still with visible balks, usually overgrown by dozen-year-old trees or herbaceous plants. Open spaces are occupied by synanthropic plant communities (Fig. 1D) and ferns are found under the treetops (Fig. 2D). Some fragments of the gully are littered (Fig. 2B). Several fox burrows are located on the right slopes with ground heaps below their outlets (Fig. 2C).

The devastation of the Lipniak gully drew the attention of residents of the Lipniak estate. In 2014, they submitted a project titled "Pedestrian and Bicycle Route Connecting the Lipniak Estate with Węglin Północny" for funding by the Lublin City Hall under the Civic Budget program. The initiative received support from the Węglin Północny District Council and 1236 city residents during a public vote. However, the project was not consulted with scientists studying human–environment interactions concerning Lublin's gullies. As a result, the project, completed in 2017, significantly impacted the ecological value of the area by altering the land's natural relief and introducing materials such as concrete, steel, and asphalt. The project covered only the construction of a concrete pedestrian and bicycle path through the second (II) section of the ravine. The route begins at Lipniak Street with a terrace cut above the right slope of the ravine, crosses it via a high drainage culvert, and then ascends the bottom of the excavation to the left slope, ending at Klepackiego Street. The 400-m-long route comprises a 2-m-wide asphalt and concrete bicycle path and a 1.5-m-wide pedestrian path made of concrete cobblestones. The route is equipped with safety barriers, benches, and lanterns (Fig. 3A, B).

As a result, the implemented project did not address the residents' needs, as they strongly prefer the pro-ecological development of gullies in Lublin. A questionnaire conducted in 2023 revealed that both representatives of the Lublin City Office (mean number of point 4.6 out of maximum 5.0) and citizens from various city districts (mean number of point 4.8 out of maximum 5) agreed that cities' gullies require greater attention in urban planning[35]. They emphasized that gullies should be developed in a manner that harmoniously combines environmental values with social needs, creating user-friendly green spaces. Furthermore, planners and managers, as outlined in the Lublin 2030 Strategy[36], highlighted that the city's development should aim to integrate urban green areas into a more cohesive system by implementing pro-ecological solutions. As the gully management policy in Lublin remains in its early stages and lacks a consistent development concept, this study can offer valuable guidance for the city's authorities. It proposes an approach that balances socio-economic development with nature conservation, providing a model that could be applied to other gullies in the city.

Methods

As a comprehensive review of source materials revealed a lack of historical documentation for the Lipniak gully, both in terms of ecological and historical databases as well as photographic documentation, the reconstruct of its development history was based on historical maps and aerial photos together with the soil sampling. The research was based on four research questions (RQs) and consisted of eight substages (S1.1–S4.2) (Fig. 4). This structure was adopted to analyze the specificity of the evolution of the Lipniak gully and its impacts on the current state as well as the factors that determine its sustainable use and should be included in the revitalization project.

Stage 1: Impact of anthropogenic modification of land use/cover in the gully vicinity

First, indicators showing the changes in land use/land cover (LULC) types in the Lipniak gully and its vicinity were adopted. Eight topographic maps (1804, 1843, 1915, 1936, 1956, 1978, 1984, 2002) at a scale ranging from 1:25,000 to 1:126,000 and six series of orthophotomaps from 1944, 1954, 1973, 1980, 1983, 2021 were used for this purpose (Appendix B). All cartographic materials and aerial images were georeferenced in accordance with the Polish National Coordinate System PL-1992 (EPSG: 2180)[37,38]. The newest available ortophotomap from 2021 from GUGiK (Head Office of Geodesy and Cartography) was used. For the remaining periods, authors independently performed orthorectification of the photos, which were then published on the Lublin City Hall geoportal. The procedure for creating historical orthophotomaps is described in details by Kuna[38]. In the case of orthophotomaps, the following LULC were assessed: buildings, roads and paved surfaces, fields, high vegetation forms (trees and shrubs), and low vegetation forms (lawns and gardens). Due to the low resolution, the rest of the maps served as illustrative and comparative material for detecting changes in the surroundings of the gully and were not subject to quantitative analyses. The obtained information was used to determine the most important impacts of anthropogenic modifications to the LULC in the gully and its vicinity. On this basis, historical land use elements that should be preserved while guidelines for the sustainable use and revitalization of the analyzed area were formulated.

Fig. 3. Pedestrian and bicycle paths across the Lipniak Gully implemented in 2015: (**A**) on the terrace and above the culvert (photo by J. Rodzik); (**B**) in the excavation on the left slope (photo by J. Rodzik) (Compiled by J. Kuna & co-authors).

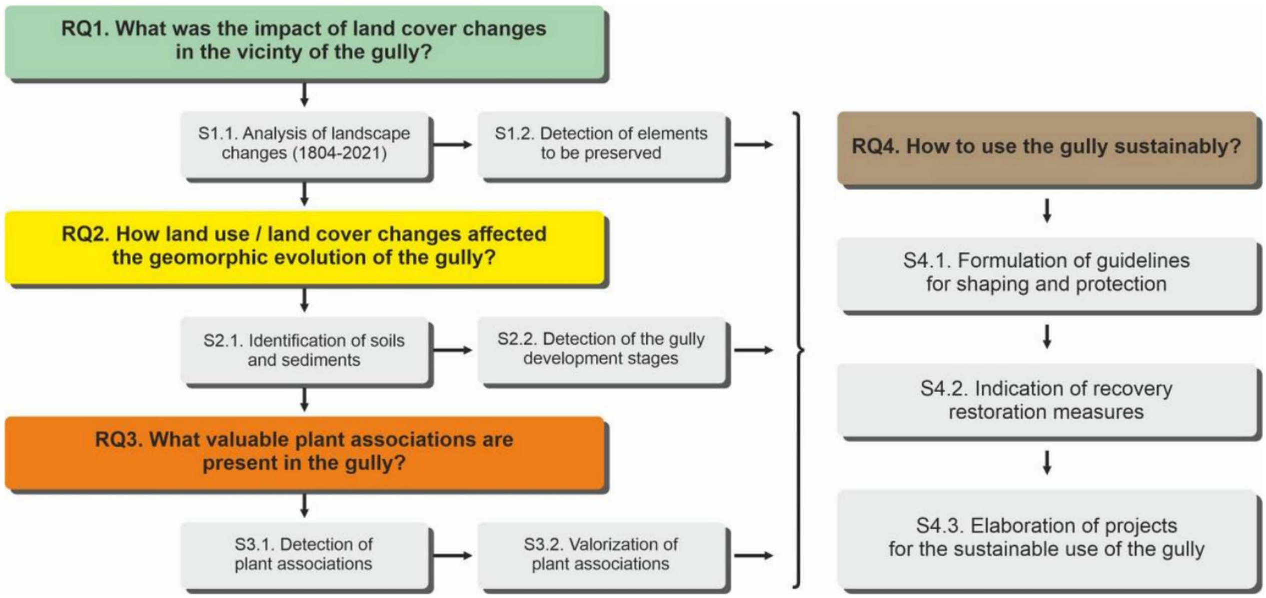

Fig. 4. Methodological framework (Compiled by J. Kuna & co-authors, using CorelDRAW 2019 & Adobe Photoshop CS6 software).

Stage 2: Land use/cover change impacts on geomorphic evolution
The identification of soil and sediment indices involved the performance of 17 drillings of sediment-soil profiles distributed in two cross-sections of the landform located 50 and 130 m from Lipniak Street (Fig. 1B, Appendix A). The research profiles were designated in characteristic places where noticeable changes in the slope inclination occurred (see Fig. 1B Investigated cross-sections). Distances between the profiles were measured by means of a tape measure, and inclinations and height differences were measured by means of a *Suunto* clinometer. The application of more advanced methods (GPS, total station, TLS) was not possible due to the presence of dense shrubs in the gully. A manual *Eijkelkamp* corer with a sampler with a diameter of 3 cm was used to collect cores with undisturbed structures from the designated profiles. The particular soil and sediment horizons were characterized in terms of color, bulk density, and structure and subjected to a test for carbonate content by means of 10% HCl. The soil units distinguished were classified according to the Systematics of Soils of Poland[39] and the international soil classification[40]. The identification of soils and sediments in the cross-sections provided the basis for the preparation of soil catenas, reflecting the direction and volume of transformations of the soil cover and land relief. This approach made it possible to reconstruct the original topographical surface[22,41]. The gully development stages were based on the identification of interactions between land use changes and geomorphological processes.

Stage 3: Values of the plant associations
Phytosociological releves were performed on the two appropriate cross-sections (transects) that are presented in Fig. 1B and were used in the soil and sediment assessments. The method was in accordance with Braun-Blaquet[42]. These studies aimed to determine the direction of secondary vegetation succession and its possible dependence on the type of substrate (soil condition) as well as the assessment of the vegetation in terms of environmental value. Besides, the species which are under legal protection in Poland were determine and characterized. The nomenclature of the plant associations was provided in accordance with the study on the vegetation of the Polish lowland and uplands[43] and of vascular plants after Mirek et al.[44].

Stage 4: Guidelines, restoration measures and projects for sustainable use
First, based on the results obtained in stages 1–3, guidelines for protection and shaping of the gully were formulated in relation to geological, ecological, cultural, social and management aspects. Then, on their basis, restoration measures were proposed to improve the current state based on the concept of gully development. This work was conducted by an interdisciplinary team with the aim of identifying all the factors that are crucial for the sustainable management of the Lipniak gully.

Results
Impact of anthropogenic modification of land use/cover in the vicinity of the gully
A comparative analysis of maps enabled us to detect major changes in the surroundings of gullies since the nineteenth century. At approximately 1800, a valley was present at the site of the present gully and was located in a forested area (Fig. 5_Ia). At approximately 1840, the valley remained overgrown by trees and shrubs, and the plateau was already significantly deforested and was likely occupied by crops (Appendix C). In 1864, the manor farm Węglin was established nearby[45] to intensify the spatial development of this area (Table 1, stage Ia). A dirt

Fig. 5. Land use structure of the Lipniak gully area; (**Ia–c**) Lipniak gully and surroundings on archival topographical maps; all maps rescaled to approx. 1:40,000; (**IIa–c**) Segment 2 on archival aerial images and contemporary ortophoto; all images resacaled to approx. 1:9000; (Compiled by J. Kuna & co-authors, using QGIS 3.16.7, CorelDRAW 2019 & Adobe Photoshop CS6 software) List of primary cartographic sources is provided in Appendix B and C.

Gully development stages; period	Valley slopes above the gully (in decline direction): L—left, R—right		Valley bottom—gully (in decline direction): B—gully bottom, L—left side, R—right side		
	Land use	Geomorphic processes	Land use	Geomorphic processes	Geomorphic effects
I a, 1864–1907	L, R—transverse-slope fields of manor farm	L, R—insignificant	B—ground road	B—washing, deep erosion	B—road cut
I b, 1908–1944	L—pasture; R—as above	as above	as above	as above	B—deepening of the road gully
II a, 1945–1959	L—pasture and fields along the slope; R—transverse-slope fields of state farm	L—rill and tillage erosion; R—as above	B—as above; L—agriculture; R—shrub	B—as above; L—tillage erosion; R—undercutting	asymmetric gully formation L—easing; R—strafing
II b, 1960–1989	L—fields along the slope; R—home gardens	L—tillage erosion; R—infiltration	B—waste; L—agriculture; R—shrub	B—aggradation: L—by tillage; R—by slump	B, L—increase; R—recession
III a, 1990–2016	L—wasteland, young trees and shrub; R—as above	L—stability; R—initial piping	B, L—wasteland; R—trees	outlet blocking, B, L—organic accumulation; R—fox pipping	outlet blockage, B, L—stability; R—fox burrows and heaps
III b, 2017-now	L—as above, concrete path in the excavation; R—as above, concrete path on the terrace	L, R—stability, washing on the excavation slopes	as above and concrete path over the culvert	as above	as above

Table 1. Formation of the section II Lipniak Gully in stages I–III, based on the collected material and comparison with various publications, mainly Rodzik et al.[53].

road was established on the floor of the dry valley running from the manor farm to a sheepfold on the other side of the Konopniczanka River valley (Fig. 5_Ib,(Table 1, stage Ib). The arrangement of arable fields has been known since the end of the first half of the twentieth century (Fig. 5_IIa; Table 1, stage IIa). On the right side of the gully, there were multistripe fields parallel to the road. On the left, in section II, there are narrow plots of land along the slope perpendicular to the road. After the 2nd World War and the political transformation, the manor farm was nationalized and partially parceled, and the PGR Węglin was established and incorporated into the territory of the city in 1959[45] (Fig. 5_Ic). In the early 1980s, allotment gardens were established occupying the first segment of the gully (Fig. 5_IIb). The along-slope fields on the left side of the second segment of the gully were cultivated by the farmers of Konopnica village at least until the next political transformation in 1989, when they were incorporated into the territory of the city (Table 1, stage IIb). Currently, allotment gardens are still present on the right bank of the gully, but buildings (estate of single-family houses) are being constructed on the left bank of the gully at the place of the former agricultural areas. In addition, trees and shrubs enter the bottom of the gully (Fig. 5_IIc,Table 1, stage IIIa-b).

The calculation of LULC change indicators showed that from the purely agricultural use of the vicinity of the gully in 1944 (71.5% fields, 28.5% low vegetation) (Fig. 6A; Table 1, stage 1b), its land use gradually changed to fields on the left bank of the gully (58%), and the mosaics of high (33.55%) and low (5%) vegetation forms

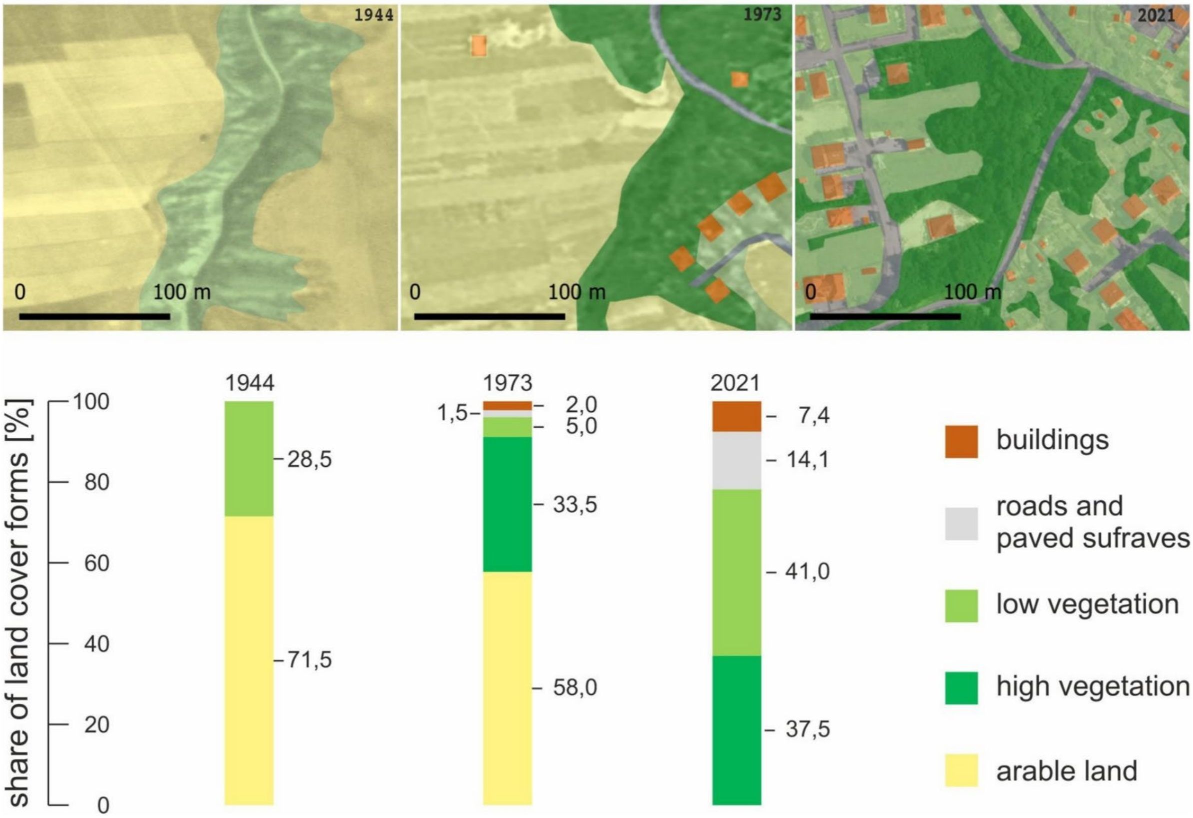

Fig. 6. The most important changes in the land use structure surrounding the Lipniak gully; (**A**) 1944, Left slope—individual farms, Right slope—post manor state farm (PGR); (**B**) 1973, Left slope—individual farms, Right slope—suburban development; (**C**) 2021, Left and Right slope—urban development (Compiled by J. Kuna & co-authors, using QGIS 3.16.7, CorelDRAW 2019 & Adobe Photoshop CS6 software); List of primary cartographic sources is provided in Appendix B and C.

paved surface and (1.5%) building (2%) on the left bank in 1973 (Fig. 6B; Table 1, stage IIb). In the present large ploughing parcels were completely replaced by mosaics of low vegetation (41%), paved surfaces (14.1%) and buildings (7.4%) (Fig. 6C; Table 1, stage IIIa-b). The share of high vegetation was comparable to that in 1973, but its location partially changed from the northeast corner to the left bank. Due to very dynamic changes in the land use pattern, no historical elements, such as buildings or field structures, were detected that should be preserved while formulating guidelines for the sustainable use and revitalization of the analyzed area.

Impacts of land use changes on geomorphic evolution of gullies

The cross-sections of segment II of the valley-gully form of the Lipniak show general similarity to letter V with evidently convex slopes. In the upper part, they usually have an inclination of 10°–15°, in the middle part, they have an inclination of 15°–20°, and in the lower part, they have an inclination of 40°–50° (Appendix A). The valley is asymmetric; the left slope has a height of 6–7 m and a lower inclination, and the right slope has a height of 8–9 m and a greater inclination (Fig. 7A,B). Five types of soils were identified in the present study (Fig. 8A). Individual types of soil occupy small patches of various lengths—sometimes only a few meters. Typical orginal luvic soils with a complex profile, A–Et–Et/Bt–Bt1–Bt2–BC–C–Ck, and a considerable depth of 1.5–2 m are particularly preserved in the upper part of the right slope. They were even aggradated by slope deposits from agricultural fields. On the left slope, in its upper part, the remnants of the original soil profile are mostly preserved. In the lower part of the left slope, an almost complete soil profile has been preserved in cross-section A, while in cross-section B, the soil has been eroded down to carbonate loess. Noteworthy in both cross sections is the significant thickness of massive arable colluvium deposited during mechanical plowing. In the gully floor, the soil profile was removed; loess is covered by slope colluvia with a thickness of approximately 1 m in the form of usually disorganized packages from slumps and locally laminated fluvial sediments.

The analysis of cross-sections and soil catenas and sediment in reference to land use/cover changes showed that the study area was subjected to complex geomorphological conditions (Table 1). The original natural landform was a dry trough-like valley (the valley shape was not either U nor V-shaped) with a depth of 5–6 m, where deep luvic soil developed on the slopes under a typical broadleaf forest. The valley in this part was characterized by climatic asymmetry, with a steep slope with sunny exposure (ESE) and a gentle slope with shaded exposure (WNW). The difference between the inclination and exposure of the slopes, and thus their humidity, is reflected in the original thickness of the soil profile, which is much greater on the right slope. Such

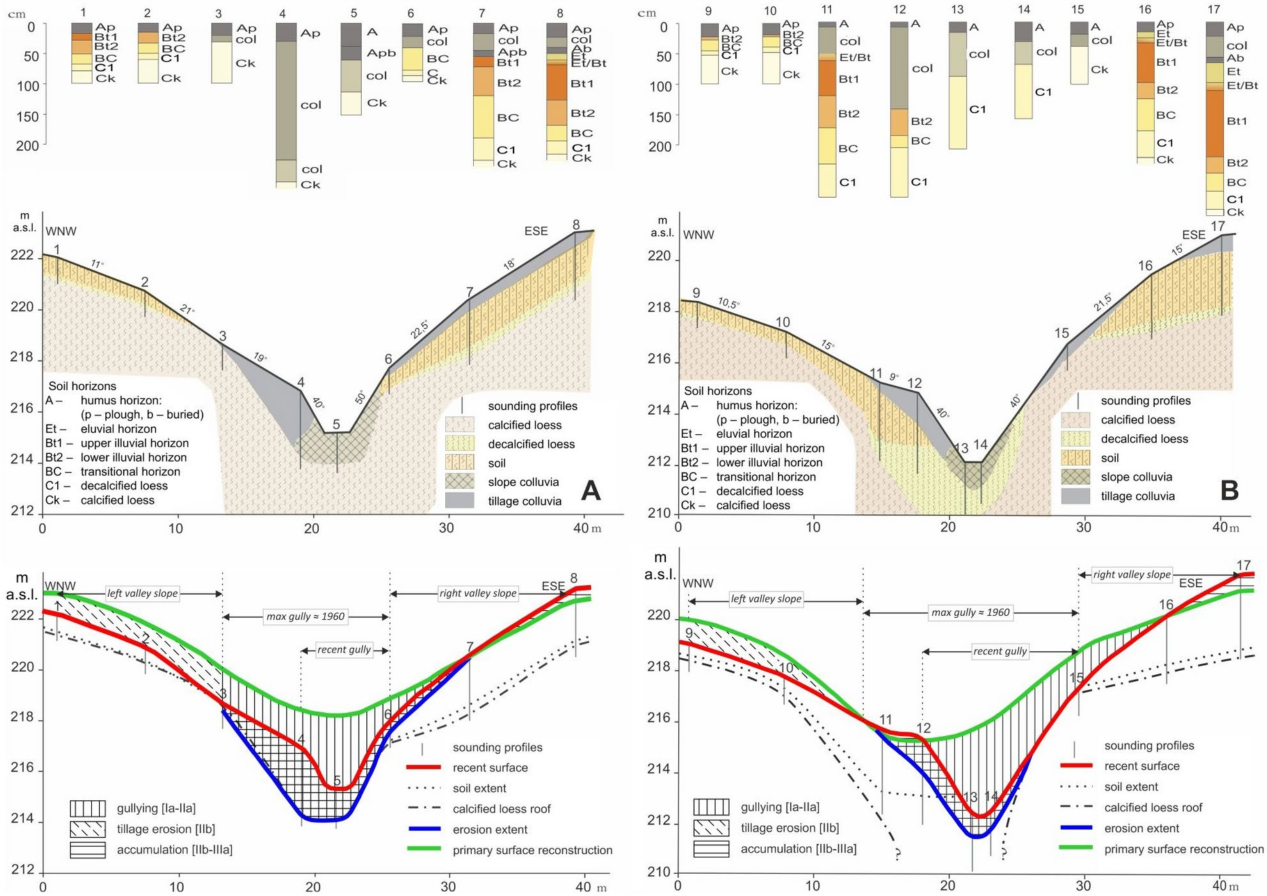

Fig. 7. (**A**) Cross-section A across the Lipniak valley form located 130 m from the road; (**B**) Cross-section B across the Lipniak valley form located 50 m from the road; Top—soil profiles and soil catena; bottom—reconstruction of the primary valley form (Compiled by J. Kuna & co-authors, using CorelDRAW 2019 & Adobe Photoshop CS6 software).

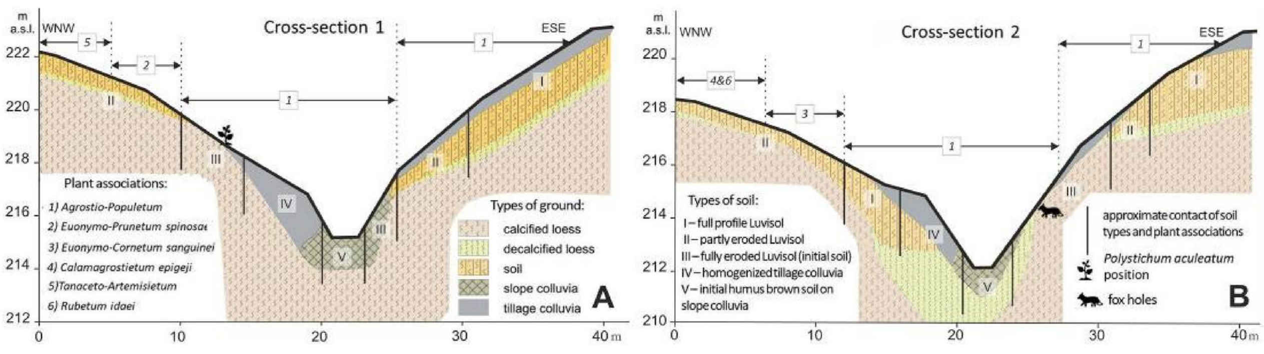

Fig. 8. (**A, B**) Plant transects along cross-sections: soil catenas and plant associations in the Lipniak valley/ gully (Compiled by J. Kuna & co-authors, using CorelDRAW 2019 & Adobe Photoshop CS6 software).

relief survived until the clearing of the forest and the commencement of agricultural and transport land use (approx. beginning of the twentieth century) (Table 1, stage Ia). The soil catena and colluvial sediments show no traces of use older than modern ones. Its beginning was associated with the establishment of the manor farm Węglin in 1864 and the creation of dirty roads. Between 1908 and 1944, the deepening of the road gully occurred (Table 1, stage Ib). Period 1945–1959 included the establishment of pasturelands and fields along the left slope and transverse-slope fields of the state farm on the right, resulting in asymmetric gully formation (Table 1, stage IIa). The main role in the transformation of land relief was played by the probable cessation of a dirt road in the 1960s soon after the area was incorporated into the territory of the city (Table 1, stage IIb).

The concentration of overland flow on the road caused its erosion and gradual deepening of the valley floor—at the final stage by approximately 4 m, i.e., at a rate of approximately 4 cm annually. Lowering the local erosion base resulted in cutting of the ravine edges and valley slopes, especially in sections I and III. Loess colluvia from gully erosion, transported by road by surface runoff, was deposited at the mouth of the ravine in the form of a fan, separating the bottom of the Konopniczanka valley and blocking its outflow. Above the fan, a pool of water with reed vegetation formed at the bottom of the valley. In the 1960s and 1970s, the area was subjected to building development, and stage IIb of gully development started (1960–1989) (Table 1, stage IIb). After the introduction of mechanical cultivation in the 1970s, farming on the lower part of the slope was discontinued. Colluvia accumulated, and an agricultural terrace developed. Its edge became the left accumulative edge of the gully. Slope colluvia with humic material accumulated on its floor, causing aggradation by 0.5–1.0 m. Stage IIIa (1990–2016) is connected with the anthropogenic transformation of the discussed valley form, which ceased its complete incorporation into the territory of the city (Table 1, stage IIIa). In 2017, the last IIIb stage of gully development started connected to the construction of the concrete path in the excavation (left bank) and on the terrace (right bank) (Table 1, stage IIIb).

Values of the plant associations

The following six plant associations were identified to determine the differences among the ecological values of the gullies (Fig. 8A, B):

(1) The aspen thickets *Agrostio-Populetum tremulae* are associated with various succession stages, mainly the terminal phase. It is a low-elevation forest particularly composed of common aspen *Populus tremula* and a low number of goat willow *Salix caprea* in the tree layer. In the shrub layer, goat willow, common dogwood *Cornus sanguinea*, and black elder *Sambusus nigra* were dominant. On the transition B of the plateau into a slope, a shrub phase developed. Under aspen thickets on the left slope of the gully with an inclination of approximately a dozen degrees and ESE exposure, a site of occurrence of the protected plant hard sheld-fern *Polystichum aculeatum* (Figs. 2E, 8A, B)

(2) Patches of the blackthorn thickets *Euonymo-Prunetum spinosae* phytocenosis occupy a small area in the northern part. On the terrace in the lower part of the slope, they occur as a forest edge surrounding aspen thickets. The contribution of herbaceous plants is scarce.

(3) The thickets of common spindle *Euonymo-Cornetum sanguinei* are distinguished by the compact occurrence of common dogwood *Cornus sanguinea*, which reaches 3 m in height. Among other trees, blackthorn *Prunus spinosa* grows in some of the patches. The forest floor layer is developed to a low degree. The association occupies small areas in the northern and central parts of the studied segment of the gully.

(4) The patch of association of wood small-reed Ass. *Calamagrostietum epigeji* occupies a small area on the plateau above the central part of the studied segment of the gully. It is characterized by almost exclusive occurrence of wood small-reed

(5) The thickets of common raspberry association of *Rubetum idaei* develops an edge of tree stands of aspen thickets, particularly those growing in the central part of the study area. In addition to the dominant red raspberry *Rubus idaeus*, a small contribution of other species from the genus bristberries *Rubus sp*. was observed.

(6) The wine with common tansy and mugwort *Tanaceto-Artemisietum* association grows on the western edge of the studied vegetation complex, where the land area is cultivated the most. The association developed in two facies. The majority of the patches constitute a typical facies dominated by mugwort *Artemisia vulgaris* and common tansy *Tanacetum vulgare*. The facies with goldenrod *Solidago gigantea* and Canada goldenrod *S. canadensis* occupy a small area in the central part of the studied segment of the gully. A systematic list of syntaxons is provided in Appendix D.

The existence of hard shield-fern on the left slope of the gully showed the unique ecological value of the site as this species in under legal protection in Poland. In addition, for ecological reasons, however, elements are numerous high vegetation forms (those that persist for more than 120 years) in proximity to gullies. In section II of the gully, there are 15 specimens of dendroflora that, based on the Regulation of the Polish Minister of the Environment[46], can be considered eligible for protection in the form of natural monuments: 11 induvial common hazel *Corylus avellana* and one each of Norway maple *Acer platanoides*, common hawthorn *Crataegus monogyna,* common hornbeam *Carpinus betulus* and crab apple *Malus sylvestris*. The slopes of the ravine in the III section, where the paved road runs, are also covered with stately trees, whose crowns meet and form a shaded green tunnel. It is a place frequented by walkers and cyclists (Fig. 2E). The charms of the place were recognized with a jury's award, in the "Space" category, in the first edition of the "Cultural Treasures of Space" poll in 2019 (http://teatrnn.pl). In the bottom of the ravine in section IV of the ravine, 2 specimens of black poplar *Populus nigra* of monumental size were inventoried (Fig. 2F) .

Guidelines, restoration measures and projects for the sustainable use of the gully

Based on the obtained results, a set of general guidelines related to five aspects, geological, ecological, cultural, social and management, was formulated (Table 2; columns A and B). These studies aimed to strengthen the recreational use of the Lipniak gully through its multifunctional use by different citizen groups and simultaneous protection of the gully in terms of geological and ecological aspects. Considering the guidelines and current state of gully development, including the structure of existing bikes and walking tracks, a set of recovery measures was proposed for the sustainable use of gullies (Table 2; Column C).

The formulated guidelines were used to elaborate upon the alternative concept of development in this area. The concept includes the management of the Lipniak gully as a recreational-tourist trail for pedestrian and

A. Aspect	B. Guidelines	C. Changes in current development
Geological	G1) Prevention of the destruction of the gully geomorphological structure G2) Soil protection	G1) G2) Do not introduce any further development changes
Ecological	E1) Protection of rare plant associations and species E2) Protection of plant associations against trampling E3) Strengthening the recreational use of the gully	E1) Cleaning of the outlet of the gully from invasive plants: Canada goldenrod, goldenrod, black locust *Robinia pseudoacacia* E1) Creation of a protection zone in the form of ecological use for the hard shield-fern E1) Cleaning of the bottom of the gully from dead branches and trees being the threat to oak plant associations undergrowth of the oak-hornbeam forest E3) Implementation of a system of wooden bridges over the gully M3) Incorporation of the gully into the city's system of green areas (ecological corridors)
Cultural	C1) Protection and exposure of historical elements	C2) Elements worthy of preservation are high vegetation forms in the proximity of the gully, especially 15 specimens of dendroflora which can be given status of the natural monuments
Social	S1) Making the area available to residents S2) Ensuring the multifunctional use of the gully by different citizens groups S3) Strengthen of education values of the gully	S1) Clearing of the bushes being the secondary vegetation especially black locust and box alder *Acer negundo* S1) Placing bicycles' racks and garbage cans next to existing rest areas (benches) S2) Creation of additional recreational infrastructure next to existed paths S3) Conducting educational walks promoting the values of the gully S3) Creation of the education path showing the history of the gully
Management	M1) Strengthening of recreational use of gully M2) Reduction of interference into natural character of the gully M3) Changes in Land Use Local Plans	M1) Incorporation of existed path into the city's cycling and walking system M2) Removal of the cracked surface of paths and replacing it with a natural surface (dirty/wood paths) M3) Introduction of a development-free zone along the gully

Table 2. Guidelines for protection and shaping of the Lipniak gully together with recovery measures.

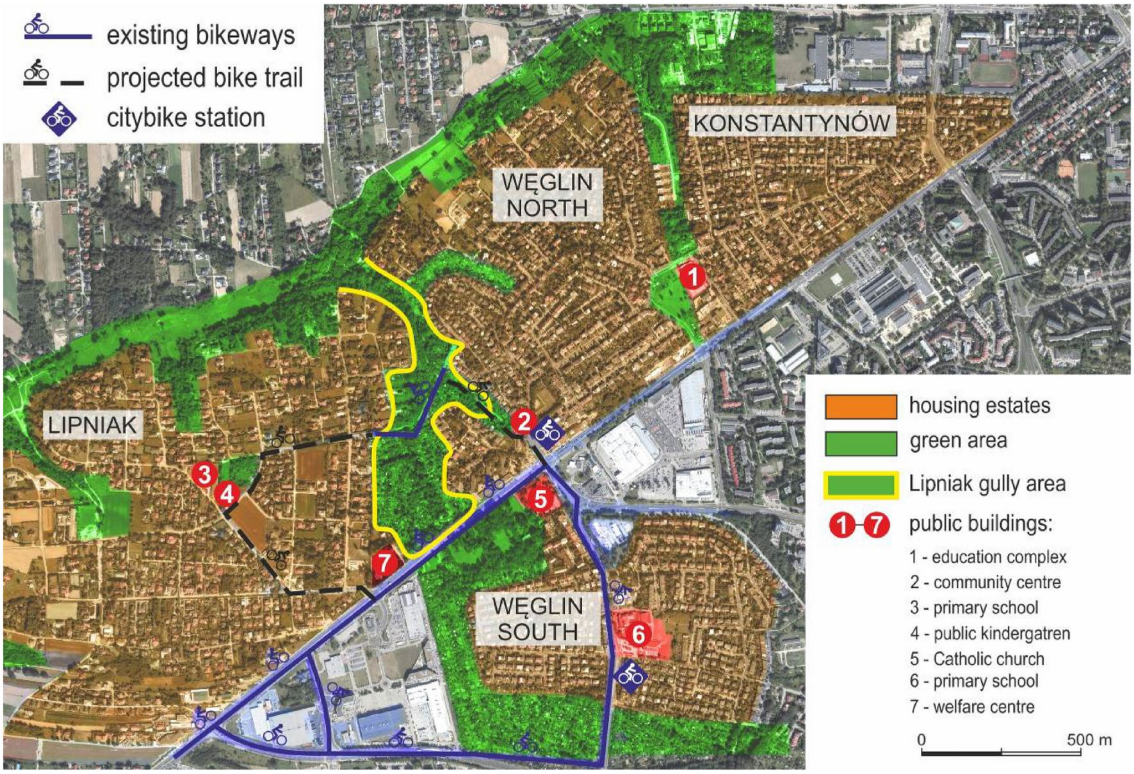

Fig. 9. Existing bike trail (purple) and proposed course of the trail (black) based on 2021 Ortophotomap (GUGiK) (Compiled by J. Kuna & co-authors, using QGIS 3.16.7 & Adobe Photoshop CS6 software) List of primary cartographic sources is provided in Appendix B and C.

bicycle traffic with respect to natural and cultural values. In contrast to existing bike paths, gully development projects assume the incorporation of pedestrian and cycling paths into existing urban systems of cycling and pedestrian paths and connections between buildings and public institutions important for districts, such as schools, churches, and community centers (Fig. 9). The planned path initially runs through the area of allotment gardens, which were adapted to the small district Park Lipniak. The trail runs to a wooden bridge with a width of 3 m, which is situated above the gully (Fig. 10). This approach prevents the destruction of the gully. Parking places for cyclists are stipulated in the project with bicycle racks and benches, as well as information and educational boards located along the planned trail. The western edge of the gully will include a jogging path equipped with

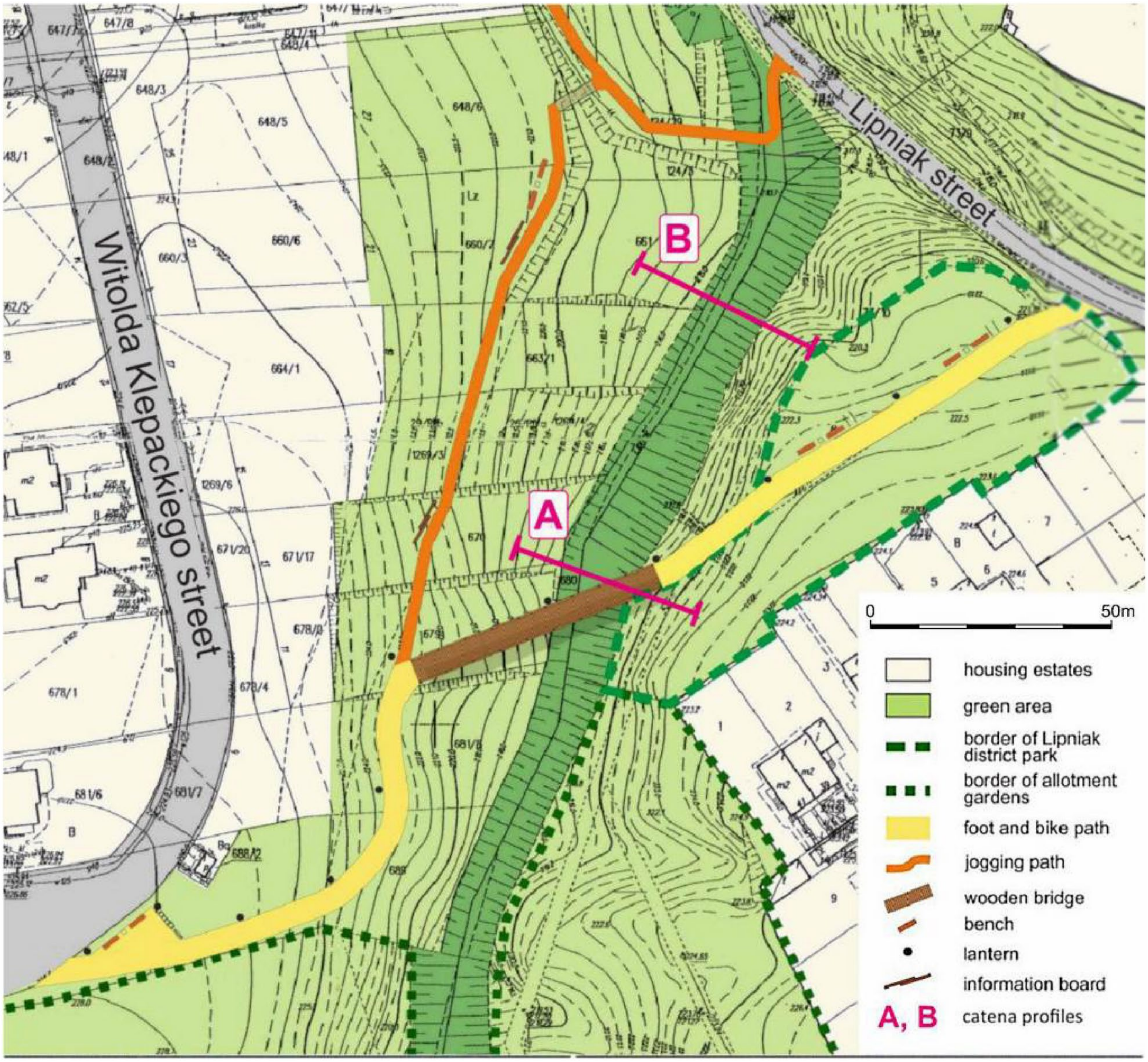

Fig. 10. Alternative project of Lipniak Gully development based on 2019 Mastermap (UM Lublin). (Compiled by J. Kuna & co-authors, using QGIS 3.16.7, CorelDRAW 2019 & Adobe Photoshop CS6 software). List of primary cartographic sources is provided in Appendix B and C.

wooden small architectural elements for running exercises and information boards. The designed paths were established around the site of occurrence of the protected plant hard shield-fern to ensure both the protection of nature and the educational value of the project.

Discussion

Urban gullies development

Research has shown that long-lasting anthropogenic modifications were the main driving factors of Lipniak gully development in the past, revealing significant interrelationships among all the indicators. Agricultural and communication use resulted in significant fragmentation and diversification of habitat conditions and directions of secondary plant succession in the Lipniak gully. Currently, the geomorphological dynamics of the study gully changes is of little importance. Based on soil profiles, it was shown that the gully was formed over a period of approx. 100 years as a road gully with changes of approx. 4 cm per year. The end of the gully development was approx. year 1960. Therefore, phenomena such as extreme events including floods after aggressive rainfall are of limited importance. In Lublin, aggressive rainfall is sporadic (approx. 1 in 10 years), and the analyzed area is not located in an area at risk of flooding. In relation to Lipniak gully, dynamic processes concern only ecological aspects such as introduction of invasive plants (including white black locust) and cumulation of foxes burrows at the bottom of the gully.

The predominant significance of anthropogenic factors in the analyzed structural development derives from the fact that it was always developed in an urban context. This finding is in line with the findings of other studies, which indicate that roads play a direct role in the formation and degradation of urban gullies[10,47]. The same was reported for other loess gully structures in Poland, as the beginning of gully formation usually coincided with the beginning of agricultural use[14]. In relation to the nonurban context, environmental factors such as humidity and dryness, as well as rainfall characteristics and soil properties, play more important roles (e.g.,[2,18,20]). In the case of vast gully areas, such as the Chinese Loess Plateau, which is the largest and most densely concentrated region of loess worldwide, escalating occurrences of extreme climate events and human activities are the most important factors influencing ecological damage in these areas[16].

Management of urban gullies

The expansion of urban building development to land with diverse relief causes a number of problems with the preservation of environmental values and adaptation to the living needs of residents. Together with sometimes disorderly construction land expansion on peri-urban areas that take up too much ecological space, this leads to a decrease in well-being. In addition, uncontrolled expansion strongly affects ecosystem service provisions in terms of reduction in runoff volume and soil erosion, along with enhancements in agricultural yield, economic output, carbon sequestration, and oxygen release[48]. Among the different land types with diverse reliefs, gullies and ravine lands are very important and remain highly researched[10,49]. Recent studies have clearly indicated the enormous potential value of gullies for their ecological and economic benefits, provision of ecosystem services and improvement of human well-being[15,48]. Therefore, different ecological aspects should be considered by designers. To do so, an integrated approach for revitalizing gullies should be taken based on the quality of the land, adoptable soil and water conservation measures and protection/shaping of permanent vegetation cover[28]. To do so, interdisciplinary research teams should be involved while discussing the concept of gully ecosystems. This approach was adopted in the present study and included providing scientific support for understanding gullies and leveraging their ecosystem functions for both nature and citizens' well-being. As gully areas can be considered ecologically sensitive complex systems, revitalization and sustainable development can be achieved only through scientific planning and socio-eco-friendly policies[49].

Lands with diverse relief developments can generally be subjected to solely nature conservation actions, both development and protection in tandem, or ecological environmental consumables[3,29]. In urban conditions, however, gullies cannot be left as enclaves of natural, unorganized greenery, despite their anti-erosion properties. The lack of control has caused such facilities to turn into wild garbage dumps and places where animals live, which are undesirable in large cities. The same was observed in the case of the studied gully, where the lack of management resulted in devastation over the last 20 years through the littering and the activity of wild animals, particularly foxes. Foxes activities caused the slope devastation together with the filling the bottom of the gully with soil. Besides, foxes are threat to pets due to the rabies spread. As a result, in Lublin foxes are usually caught and transferred.

The devastation was also carried out by a man who treated the ravine as a dumping ground for garbage, bulk and plant remains from nearby allotment gardens. Therefore, the protection of perennial vegetation and wildlife along with ecotourism can be considered the best option for the development of ravines[49], especially in relation to cities. The same was proven in the present study, as the optimal form of development for the Lipniak gully is to promote recreation together with nature protection to ensure its use by different user groups. Based on the analyzed example, a good solution also seems to be to develop allotment gardens or other forms of urban greenery surrounding gullies to facilitate infiltration and prevent the concentration of surface runoff.

Limitations and advantages of presented method

In relation to the spatial analysis limitations used to reconstruct historical changes in LULC, the map from 1843 had a low spatial resolution compared to the other materials, which may cause potential errors and uncertainties. Furthermore, we are aware that the topography of pre WW2 maps did not always accurately reflect reality, which may also lead to potential errors and uncertainties. Thus pre-WW2 cartographic material was used mostly as a qualitative source of information on the LULC changes. The quantitative study is limited to post-WW2 aerial images of resolution 1 m per pixel or higher, which, in our opinion, is sufficient for reasonable LULC change analysis when compared to modern spatial data (ortophotomap, BDOT10k database, OSM, LiDAR). The limitation of the soil assessment concerns the use of drilling methods rather than excavations, which is why there are no photos of the profiles. Additionally, the two soil profiles are insufficient for modelling the original surface in three dimensions. In relation to plant valorization, the greatest limitation is the lack of access to the upper part of the gully (due to private land) covered with rich vegetation. This area potentially holds high ecological value worth protecting and should be considered in the revitalization project.

Despite of this technical shortcoming, elaborated method can be perceived as a model for finding solution in urban planning especially in relation to the unique environmental structures for which there are no previous databases or research studies. As so, the assessment of the LULC impact on geomorphic evolution based on the comparison of historical imageries together with the soil and sediments identification can be used. On this basis, the unique and valuable geological, ecological, and cultural elements can be determine and thus preserve and/or sustainably shaping. Even though the method was tested in relation to loess gully, it can be easily adopted to other unique environmental structures located in urban areas such as dry valleys[22,41]. The advantages of the method as a model also derived from the fact that the integrated approach for revitalizing gullies was proposed, taking at the same level of importance environmental and social aspects. To successfully replicate the proposed method, it is essential to consider context-specific factors for each location. First, the current dynamics of geomorphological structure development must be assessed, as they may pose risks to urban development or have minimal impact, as observed in the case of the analyzed gully. Second, constraints arising from spatial plans and local legal provisions, such as protected species and planned land development, should be incorporated when formulating guidelines and restoration measures. Finally, social preferences should be evaluated to align planned infrastructure with the needs of local residents. This balanced approach can ensure socio-economic development while conserving natural resources. Moreover, as the gully management policy in Lublin remains in its early stages and lacks a consistent development concept, this study can offer valuable guidance for the city's authorities. It proposes an approach that balances socio-economic development with nature conservation, providing a model that could be applied to other gullies in the city and analogous situations in Poland. Such examples are Jarosław, Hrubieszów and Krasnystaw which are located on loess bedrock but are less threatened by the formation of gullies due to lower denivelations than in Lublin. Gully erosion, on the other hand, is a major problem for the small town of Kazimierz Dolny, located on the opposite end of the Nałęczów plateau from Lublin[8,9].

Summary and conclusions

The study on the development of the Lipniak gully enable to identify the origins of the gully, the causes, history and rate of development, as well as changes in use and habitat conditions for secondary plant succession. The Lipniak Gully was created within the boundaries of Węglin Manor, established in 1864, as a result of the cutting of a dirt road by linear erosion. Its dynamic development lasted only approx. 100 years, with a dredging rate of approx. 4 cm-1·year. As a result of differences in use, four sections developed, one of which remained undeveloped. For about 30 years, it was the boundary of different environments: a housing estate on the right and farmland on the left. Following the incorporation of arable fields into the urban area, the area was not commercially exploited for several years. As a result of secondary plant succession with invasive species developed. On the other hand, in a place where the soil had been removed by tillage erosion, a stand of the strictly protected fern hard shield-fern appeared on the carbonate substrate. However, left unattended, the gully area was devastated by rubbish dumping and the digging of burrows by foxes. The development project completed in 2017 did not fully address environmental and social potential of this area. Presented study revealed the need for strengthening the recreational use of gullies through multifunctional use by different citizen groups and for simultaneous protection of gullies in terms of geological and ecological aspects. This can be achieved by legal protection of valuable plants and animals and the introduction of small-scale and nature-friendly forms of infrastructure (nature trail, cycle paths, nordic walking). This direction of action enables gully development and use in accordance with the sustainable development concept, which focuses on equal economic growth that generates wealth for all without harming the environment. The presented approach can be used as an example of the development of similar gully systems in Lublin city as well as other cities that are straggling with intensive suburbanization that affects geomorphological components. In urban conditions, gullies cannot be left as enclaves of natural, unorganized greenery. The lack of control has led such facilities to turn into wild garbage dumps and places where animals live. The protection of perennial vegetation and wildlife along with ecotourism can be considered the best option for the development of gullies in relation to cities.

From an upscaling perspective and in relation to the Nature-Based Solutions (NBS) concept, the pro-ecological development of gullies aligns with Type 2 NBS, as defined by Dumitru and Wendling[50]. This category refers to the sustainable management and natural enhancement of existing elements of urban green and blue infrastructure, specifically the subtype: green and blue infrastructure elements. According to the IUCN classification[51], such solutions address key global challenges, including socio-economic development, human health, ecosystem degradation, and biodiversity loss. However, publications on the pro-ecological management of dry valleys and gullies as NBS interventions remain scarce. A Scopus search conducted on 13 January 2025 (criteria: NBS AND gullies/gully) identified only 10 relevant documents. Among these, only one study[52] discussed the use of trees on gully slopes as a bioengineering method for soil protection. Thus, this paper makes a significant contribution to the ongoing discussion on the upscaling potential of pro-ecological management of dry valleys as a type of NBS.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Author contributions
Jan RODZIK: Conceptualization, Methodology, Validation, Investigation, Resources, Writing—Original Draft, Writing—Review & Editing, Supervision Beata ŻURAW: Conceptualization, Investigation, Writing—Original Draft Barbara SOWIŃSKA-ŚWIERKOSZ: Methodology, Investigation, Writing—Original Draft, Writing—Review & Editing Jakub KUNA: Software, Formal analysis, Investigation, Resources, Writing—Original Draft, Writing—Review & Editing, Visualization Małgorzata SOSNOWSKA: Investigation, Writing—Original Draft, Visualization Marek PODSIEDLIK: Methodology, Investigation, Resources, Writing—Original Draft.

Declarations

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to B.S.-ś.

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