Article

The Late Quaternary Evolution of the Upper Reaches of Fluvial Systems in the Southern East European Plain

Andrey Panin [1,2], **Olga Borisova [1]**, **Evgeny Konstantinov [1]**, **Yury Belyaev [2]**, **Ekaterina Eremenko [2]**, **Andrey Zakharov [1]** and **Aleksey Sidorchuk [2,*]**

[1] Institute of Geography Russian Academy of Sciences, Staromonetny lane 29, 119017 Moscow, Russia; a.v.panin@yandex.ru (A.P.); olgakborisova@gmail.com (O.B.); eakonstantinov@yandex.ru (E.K.); zaanleo@gmail.com (A.Z.)

[2] Faculty of Geography, Lomonosov Moscow State University, Leninskiye Gory 1, 119899 Moscow, Russia; yubel@mail.ru (Y.B.); eremenkoeaig@gmail.com (E.E.)

*   Correspondence: fluvial05@gmail.com

Abstract: Networks of dry valleys (or balkas) and hollows in the upper reaches of fluvial basins in extraglacial areas in the Penultimate Glaciation (Marine Isotope Stage 6—MIS 6) regions of the East European Plain demonstrate clear incision/aggradation rhythms corresponding to global glacial/interglacial climate cycles. The first phase of each incision/aggradation rhythm began after the global glacial maximum and was characterized by a cool and humid climate, permafrost and sparse vegetation, when high surface runoff and active linear erosion formed a dense network of gullies. The second phase occurred at the glacial–interglacial transition and the subsequent interglacial period with its warm and humid climate and dense vegetation. This phase was distinguished by the partial filling of fluvial forms with slopewash deposits, the transformation of gullies into dry valleys (balkas) and the subsequent stabilization of fluvial forms marked by the formation of mature soils on the sides and bottoms of balkas. The third phase of the rapid accumulation of balkas developed during the cold and dry part of the next glacial epoch, resulting in the balkas becoming shallow hollows filled in with sediments. The last full incision/aggradation rhythm occurred in the late MIS 6 to mid-MIS 2. The erosion network formed during the late MIS 6 was almost completely filled by mid-MIS 2, and its manifestation in the modern topography is limited to a network of shallow hollows in the upper parts of the fluvial systems. The modern (incomplete) incision/aggradation rhythm began in the late MIS 2 and caused the formation of the modern erosion landscape in the upper reaches of fluvial systems. This rhythm is now in the stabilization phase, and the main accumulation phase of this rhythm is still far in the future.
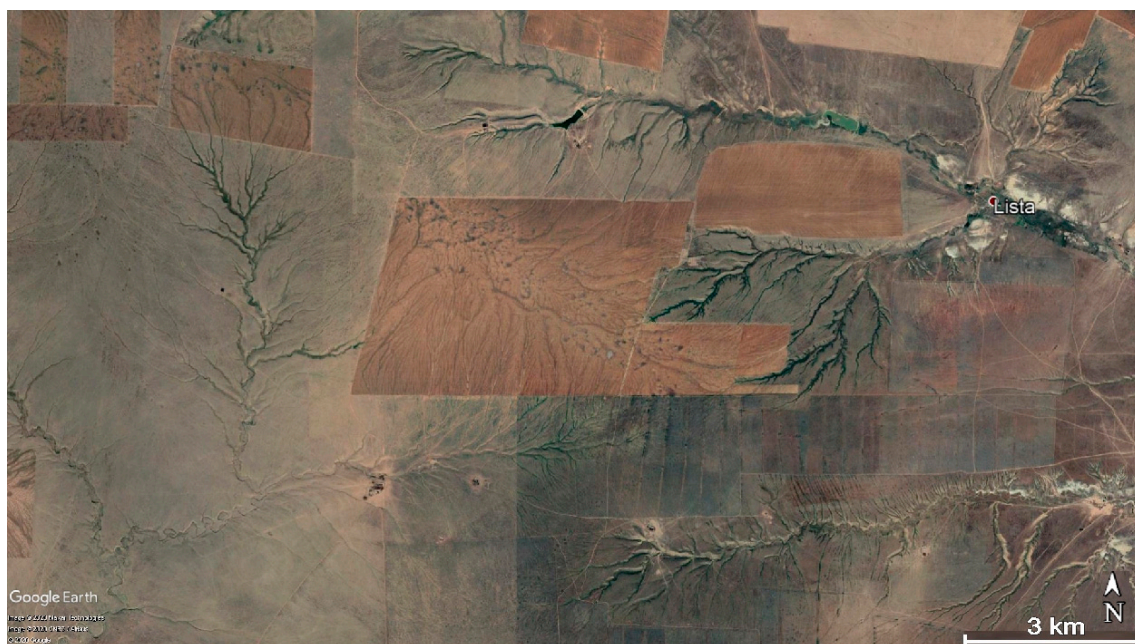
Keywords: dry valley; balka; hollow; incision/aggradation rhythm; glacial/interglacial cycle; MIS 6; MIS 2; Holocene

1. Introduction

A fluvial system is a network of interconnected channels formed by ancient and modern water streams in the course of a long morphological evolution [1,2]. The alluvial and non-alluvial sediments deposited in a fluvial system, along with their morphology, represent the "memory" of the system [3]. This memory can be used to reconstruct the evolution of a fluvial system governed "either by intrinsic change of the landform itself, or by a progressive change of an external variable" [4].

The investigations of the evolution of river paleochannels date back to the late 19th century [5,6]. Information on the paleochannel morphology and alluvial deposits has been widely used in quantitative paleohydrology, beginning with investigations conducted in the 1950–60s by Dury [7–9], Volkov [10] and Makkaveev [11]. The studies mainly concerned the morphology of Quaternary paleochannels and structures of alluvial deposits of different ages. The evolution of the fluvial topography of the largest rivers of the East European Plain (Volga, Don and Dnieper) was described in detail in the fundamental works by Goretsky [12–14], Obedientova [15] and Grishchenko [16]. In recent decades, due to the progress in dating methods, the absolute geochronology of the Late Pleistocene incision/aggradation rhythms was established in river valleys over Central and East Europe [17,18].

The upper reaches of the fluvial network include dry valleys ("balkas" in Russian terminology) and networks of gentle hollows located closer to water divides (Figure 1). These characteristics have received far less attention from researchers. Gregory [19,20] summarized the studies into the structures of hydrographic systems and concluded that it is preferable to consider the entire channel network, including both permanent and temporary watercourses, rather than a hydraulic network consisting only of permanent streams. Gregory [19,20] pointed out that there is a possible relationship between the abnormally small sizes of modern watercourses, as compared with the ancient channels of the same rivers, and the presence of dry valleys (balkas) that are not occupied by permanent streams: both can reflect a significant reduction in water flow.

Figure 1. An example of a territory with the highest density of ancient erosional dissection by systems of dry valleys (balkas) and hollows (ancient "badland" in Kalmykia, south-eastern East European Plain; 47°26′ N; 44°21′ E). The gentle morphology of hollows is evident from their abundance in agricultural fields, while balkas limit the boundaries of cultivated lands.

The erosion forms that make up the upper reaches of the fluvial systems account for more than 90% of their total lengths; therefore, their morphology and distribution deserve special attention. A number of studies have been published regarding the geological composition and history of dry valleys (balkas)—hollow networks, both buried and renewed by modern erosion, in the East European Plain [21–24] and in other regions of Europe [25–28]. However, no synthesized model of their development in relation to climate rhythmicity has been suggested so far. The aim of this study is to establish the correlation between the incision–aggradation phases in the upper courses of fluvial networks and climate changes in the framework of glacial–interglacial cycles in the Late Quaternary.

We provide new data on the morphology and geological composition of several balkas in the southern half of the East European Plain and reassess some published data on hollow systems, which allows us to reconstruct the evolution of the upper reaches of fluvial networks in the extraglacial regions of the East European Plain since late MIS 6 (i.e., over the last 140 ka).

2. Materials and Methods

2.1. Geographical and Geomorphological Setting

The study area includes the southern part of the East European Plain within the Russian Federation, between 52° N and North Caucasus uplands at 45° N. The area lies outside the boundaries of the Penultimate (Moscovian, Marine Isotope Stage 6—MIS 6) Glaciation, and most of it was not covered by ice sheets during the entire Quaternary period [29]. The present-day climate is semi-humid in the north (forested steppe vegetation with 400–500 mm of precipitation per year) and close to semi-arid in the south (dry steppes with annual precipitation only 200–250 mm in the pre-Caucasus uplands).
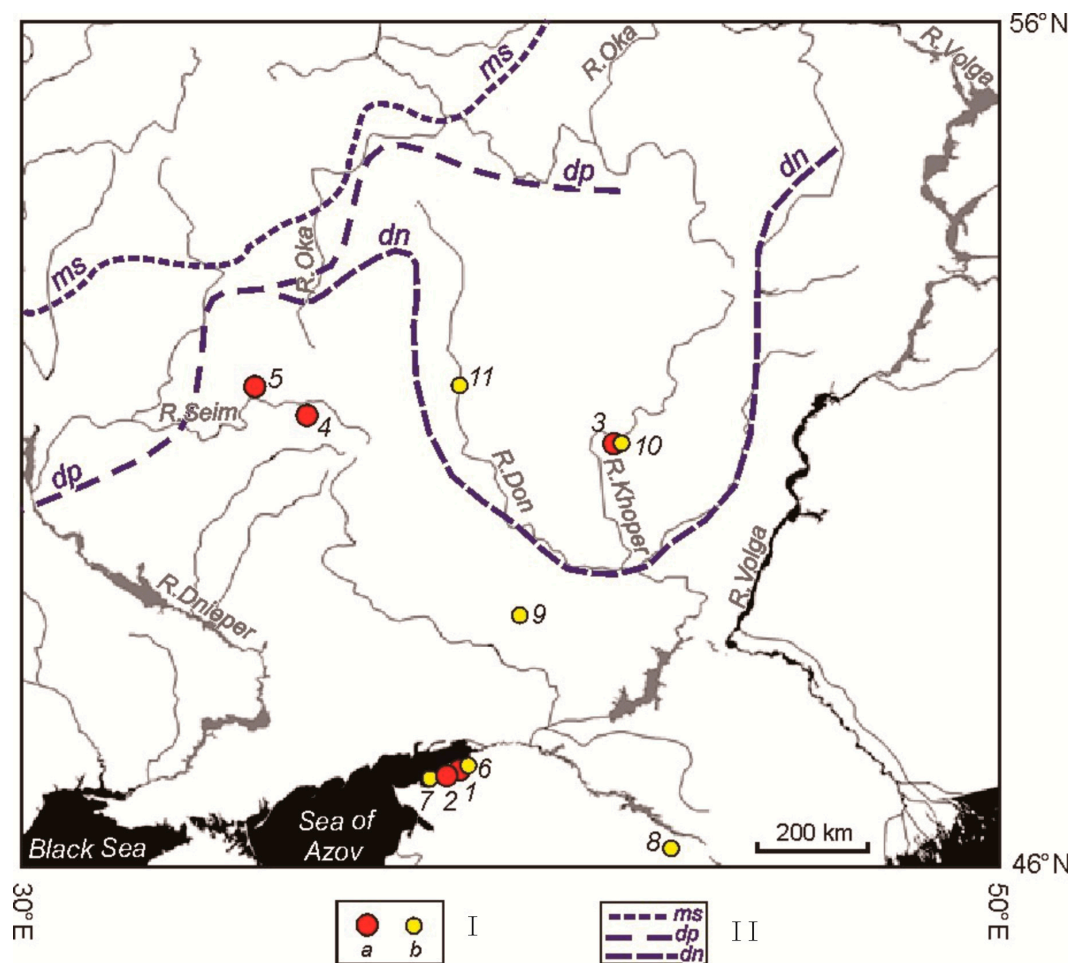
One of the most interesting topographical features in this territory is the widespread occurrence of networks of dry valleys (balkas) and hollows. Balkas have lengths in the range of 1–15 km, widths of up to several hundred meters at their mouths and depths of up to 10–15 m. At present, these systems mostly only drain water during the snow thaw period or after heavy rains. Dense grass vegetation usually covers their bottoms and slopes, meaning that in pristine conditions, erosion is negligible there. Balkas are usually continued by shallow hollows up to water divides. The spatial pattern of hollow systems in the upper parts of drainage basins suggests that these forms are also of fluvial origin, representing buried parts of the erosion network [21,30]. Within the study area, three main types of hollow networks may be distinguished: (1) dendritic systems including a central (trunk) hollow and its tributaries, (2) subparallel systems and (3) single hollows. The systems of hollows always follow the general surface inclination, with their depths and widths increasing downslope.

The relative lengths of balkas and hollows within a catchment gradually change from the northwest to southeast of the study area: the density of hollow networks increases, while the density of balka networks, in contrast, decreases in this direction [21]. The regular spatial pattern of the balka–hollow pairs indicates a single process of their formation and, probably, the similarity of deposits filling in these forms.

To reveal the history of the upper reaches of fluvial networks in the entire region, we conducted geomorphological surveys in a number of representative balka–hollow systems. All investigated case studies were located in three areas (Figure 2):

1.　The coastal area of the Taganrog Bay of the Sea of Azov;
2.　The Khoper River basin (a tributary of the Don River);
3.　The Seim River basin (a tributary of the Desna River, Dnieper River basin).

The rationale for choosing the first area was to study the response of the erosion networks to climatic as well as base level variations caused by global sea level change. The last two areas are located deep in the continental interior and may be considered to be developing under climate control independently of sea level change.

Figure 2. Location map. I—Studied sites: 1—Razvilnaya balka (dry valley), 2—Port-Katon buried balka (coastal outcrop), 3—Perepolye balka, 4—Kukuyevsky Log buried balka (Aleksandrovsky quarry), 5—Kramskoy Log balka; b—other sites referenced in the text: 6—Semibalki buried balka (coastal outcrop), 7—Shabelskoye balka, 8—Kazgulak balka, 9—Berestovaya balka, 10—Khoprets balka, 11—Pokrovsky Log balka. II—Glacial boundaries (adapted from [29]): ms—Moscovian (MIS 6), dp—Dneprovian (MIS 8?), dn—Donian (MIS 14?) glaciations.

2.2. Methods

To study the geographical distribution of hollows, satellite images of Google Earth Explorer (version 4.3) with a resolution of 2 to 15 m were used. Balkas and hollows are most clearly expressed in ploughed arable lands that are free of vegetation.

Each of the study sites was surveyed using Differential Global Positioning System (DGPS) topographic profiling, by drilling infill sediments and by examining available outcrops. Several topographic profiles were positioned along and across each balka and continuing hollows, and several boreholes were drilled on each cross-section to establish the composition of deposits over the entire balka width. Samples for pollen analysis and for dating by radiocarbon and Optical Stimulated Luminescence (OSL) methods were taken where appropriate. Soil complexes (SC) in the outcrops were identified according to the typology of the fossil soils in the region [31,32]. The paleogeographic reconstructions based on palynological data, especially those using the paleofloristic method [33–35], provided the landscape–climatic background for the geomorphological investigations.

The key instrument for assessing the geochronology of ancient erosion features in the Azov Sea area is loess–soil stratigraphy. Layers of loess of different ages are separated by horizons of well-distinguished fossil soils, presumably formed during interglacial and large interstadial intervals

of the Pleistocene, correlated with warm marine isotope stages and substages [31,32]. It is possible to identify the specific features of paleosoils of different ages based on their typical morphology and correlation with the chronostratigraphic scheme of loess–soil series of the East European Plain [31,32].
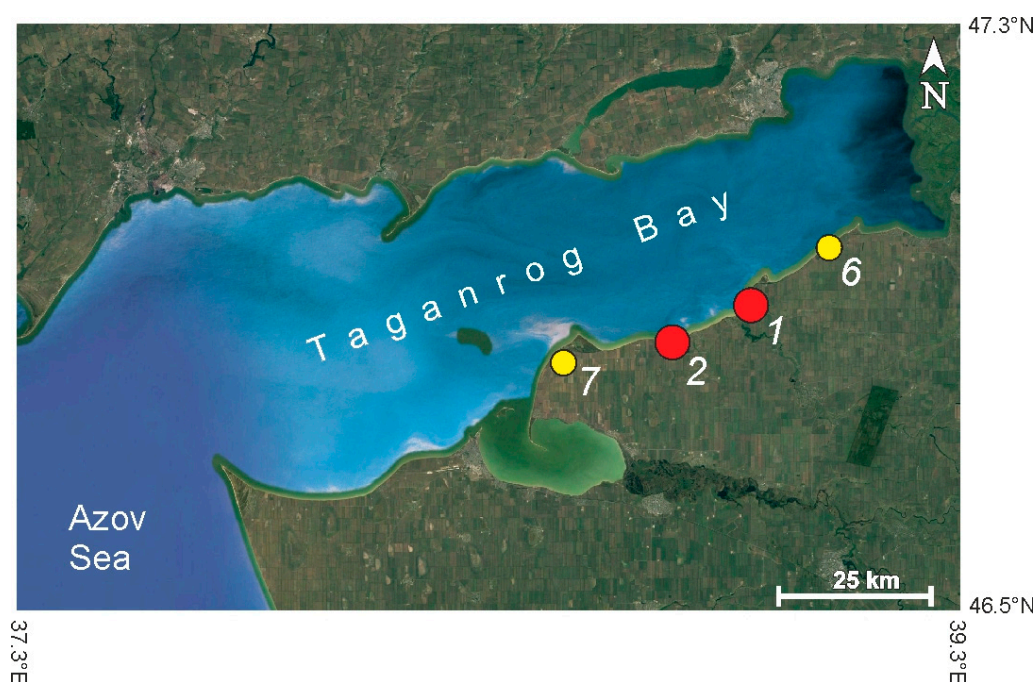
According to this scheme, the following paleosoils and soil complexes (SC), including several paleosoils of close age, were distinguished in the outcrops (from top to bottom): Bryansk paleosoil (Br) corresponding to the Bryansk Interstadial, MIS 3, app. 29–57 ka; Mezin SC (Mz) with the main Salynsk (Sl) phase, corresponding to the Eemian/Mikulino Interglacial, MIS 5e, and the younger Krutitsa soil (Kr) tentatively correlated with substage 5c; Kamenka SC (Km) with the main phase correlated with the MIS 7 interglacial; Inzhavino paleosoil (In), with the main phase probably correlated with the MIS 9 interglacial; and Vorona SC (Vr), with the main phase probably correlated with the MIS 11 interglacial. The dating of paleosoils older than Mezin SC is hypothetical and based on the general glacial–interglacial stratigraphy of the East European Plain, on paleomagnetic data and on fossil pollen and faunal remains from loess and soils, as well as from underlying lagoon-alluvial deposits [31,32,36].

3. Results

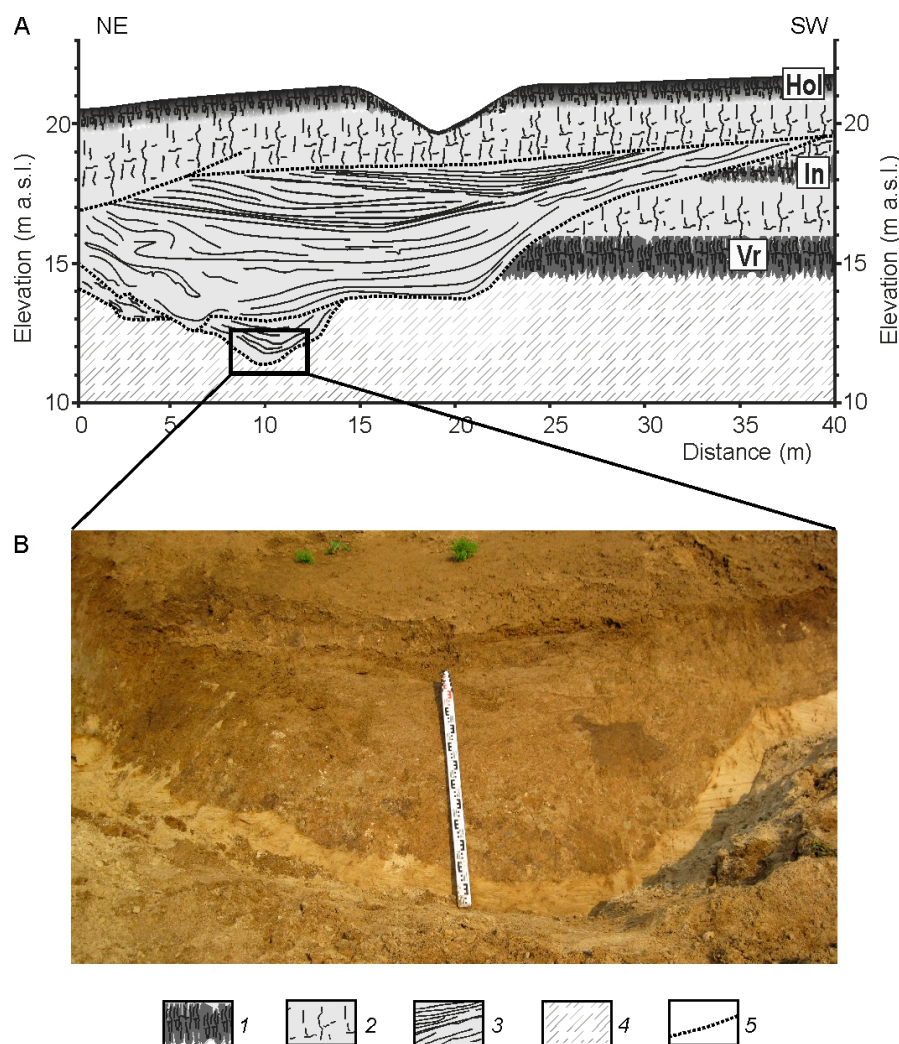### 3.1. The Taganrog Bay Coastal Region

The south-eastern coastal region of the Taganrog Bay is a loess-covered flat or slightly undulating lowland with a low drainage density of permanent flows. The territory has a gentle slope (1–2°), generally in the north-western direction. Interfluves are covered by a dense dendritic network of hollows. The hollows are poorly expressed in the topography; they have a considerable width (up to 100 m) but are only a few meters deep. Nevertheless, the hollows are clearly visible on satellite images [37].

The steep cliffs of 25–45 m in height that are typical along the southern shore of the Taganrog Bay make it possible to study the structure of the loess–soil formation in natural outcrops and to correlate fossil soils in cores to provide age estimations of buried and modern erosion forms. Konstantinov et al. [38] reported on ancient erosion forms at Semibalki and Shabelskoye (see Figure 3 for location).

Figure 3. The position of the studied and referenced sites at the south-eastern coast of the Taganrog Bay of the Sea of Azov (see Figure 2 for the key).

Semibalki is the coastal outcrop of one of the hollows that form a dense network over the area. The buried balka exposed in the coastal outcrop has a width of about 30 m and a maximum depth of ~7 m and penetrates through Inzhavino and Vorona SC into the lagoon and alluvial deposits with early Tiraspolian fauna of the Middle Pleistocene [38]. A narrow erosion furrow which is about 1.5 m deep is incised into its bed (Figure 4), indicating the complicated erosion evolution of this feature. The infill of the buried balka does not contain any well-defined fossil soils. Therefore, the age of this buried erosion feature remains unclear, except that it is obviously younger than Inzhavino SC [38].
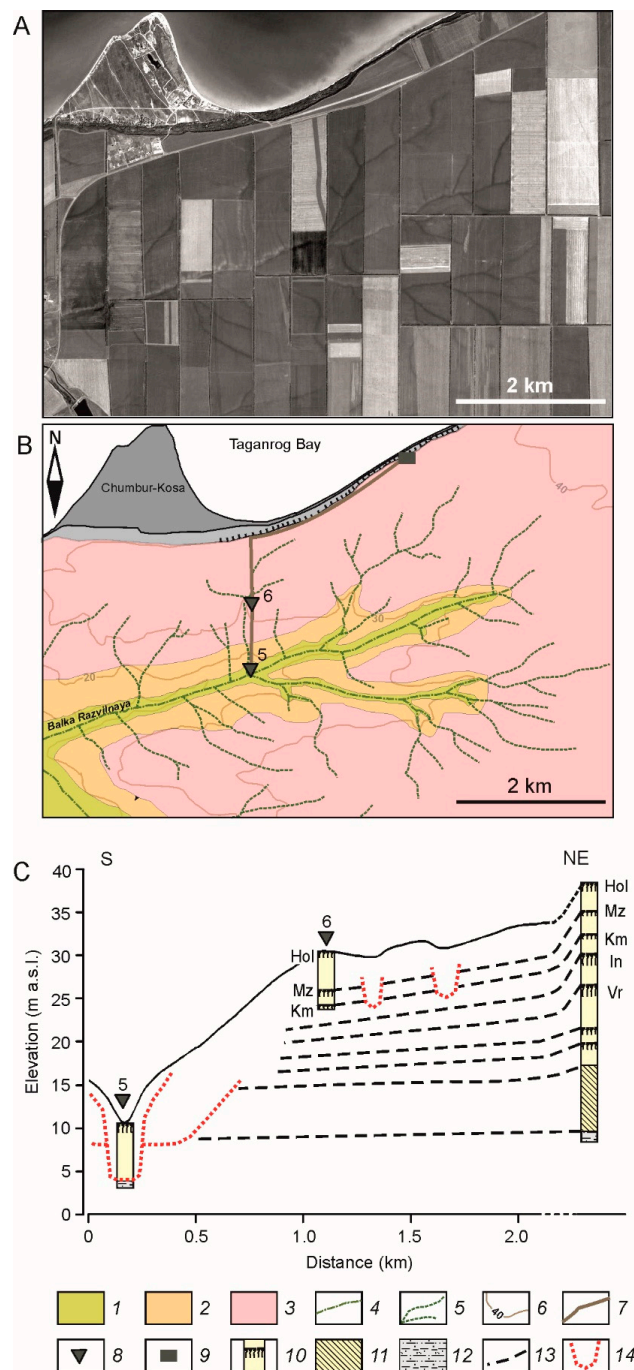

Figure 4. Buried erosional features in the coastal outcrop at Semibalki. (**A**)—Scheme of the buried balka with erosion furrow (adapted from [38]). 1—Soil complexes, 2—loess horizons, 3—loam deposits, 4—riverine sand and lagoonal clay, 5—boundaries of lithological units; Hol—Holocene soil, In—Inzhavino paleosoil, Vr—Vorona soil complex (SC). (**B**)—An erosion furrow cut into the bottom of the balka. Photo by E. Konstantinov.

To specify the Late Quaternary erosion history, we examined two more cases of ancient erosion forms: Razvilnaya (Chumbur-Kosa) and Port-Katon (Figure 3).

Razvilnaya balka near the Chumbur-Kosa promontory provides a typical example of a balka–hollow system (Figure 5A,B). The catchment area of the balka is 27 km², its length is 8.5 km, and the total length of the hollows is 68 km, which gives a total drainage density of 2.8 km·km^{-2}. In the watershed, the upper 15 m of the geological section represents a loess–soil sequence containing the full set of interglacial soils from the Mezin to the Vorona SC (Figure 5C). The base of the loess-soil cover at

about 20 m comprises lagoonal silty sands of the Early Pleistocene, according to faunal remains (for references, see [36]), that constitute the geological basement of the area.
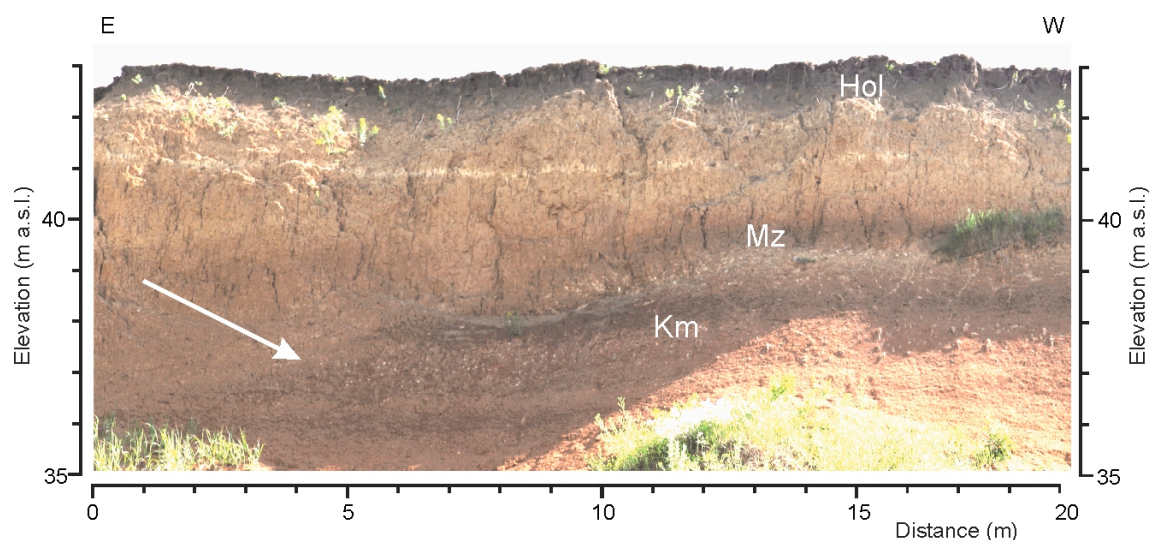

Figure 5. Razvilnaya balka–hollow system near the Chumbur-Kosa promontory. (**A**)—satellite image, (**B**)—geomorphological map, (**C**)—geological section (see location at B). Key: 1—balka bottom, 2—balka slopes, 3—interfluves, 4—thalweg of the balka, 5—hollows, 6—altitude above sea level (m), 7—studied geological profile, 8—cores, 9—studied coastal outcrop, 10—loess–soil sequence (Hol—Holocene soil, Mz—Mezin soil complex, Km—Kamenka SC, In—Inzhavino paleosoil, Vr—Vorona SC), 11—loess-like loam, 12—lagoon and alluvial deposits with early Tiraspolian fauna, 13—estimated layer boundaries, 14—erosional contacts.

In the balka bottom, the uppermost two meters of sediments are humus-rich Holocene deposits. At the depth of 2.0–4.8 m lies unlaminated loess-like loam with no signs of pedogenic transformation. It is underlain by spotty loam with unclear lamination–solifluction deposits. The lower bed at a depth of 6.6 m makes sharp erosional contact with underlying laminated silty sands—the Early Pleistocene lagoonal deposits. The balka infill does not contain both interglacial Mezin (MIS 5) and interstadial Bryansk (MIS 3) SCs, which means that the last major phase of incision occurred during MIS 2. The composition of the balka sedimentary infill evidences that the incision stopped in MIS 2 and was followed by aggradation. Most of the filling sediments (4.6 m of the total 6.6 m) were accumulated before the onset of the Holocene. In the Holocene, the aggradation trend continued, but accumulation rates decreased significantly.

The Port-Katon section (number 2 in Figure 3) is located in the highest part of the coastal cliff of the Taganrog Bay (40–45 m). For about 80 m along the coast, loess horizons alternating with fossil soils are exposed in the cliff above underlying marine sediments. Within the outcrop, an erosion feature (buried balka) about 20 m wide and 4 m deep is incised into the loess layer separating Mezin and Kamenka SCs and penetrating Kamenka SC (Figure 6). Salynsk soil of Mezin SC (MIS 5e) descends from the ancient watershed to the sides and bottom of buried balka. Several additional fossil soil horizons are clearly distinguished within the sedimentary fill in the buried balka. We assume that these soil horizons belong to the later stages of Mezin SC formation, such as Krutitsa paleosoil (MIS 5c). The nature of the erosional contacts and the texture of the deposits and fossil soil horizons within the infill of the buried balka allow us to suggest that this erosion feature was formed before MIS 5 (presumably, at the end of MIS 6) and was mostly buried during MIS 5.

Figure 6. Coastal outcrop at the site Port-Katon. Photo by S. Timireva. Hol—Holocene soil, Mz—Mezin SC, Km—Kamenka SC; the arrow points to the erosional contact.

In general, in the eastern coastal regions of the Sea of Azov, loess accumulation during glacial epochs mainly resulted in the general aggradation of the Earth's surface, the preservation of the main morphological features and the smoothening of the microtopography. The oldest erosion features that may be seen in the topography as gentle hollows were formed as early as the end of MIS 6. The most intensive erosion presumably occurred at the end of MIS 2, when all existing balkas and hollows of this region were formed or rejuvenated.

3.2. The Khoper River Basin

In the Khoper River basin (Figure 2), as well as in the Don basin as a whole, the density of balka–hollow systems is much lower than in the eastern coastal region of the Sea of Azov (up to 1.7 km·km^{-2}) (Figure 7). In this area, we studied one of the typical dry valleys—Perepolye balka (Figure 7).

Figure 7. Khoper key area. Perepolye (1) and Khoprets balkas (2), which are discussed in the text.

The Perepolye balka (catchment area 41.7 km^2) is situated near the town of Povorino on the southern bank of the River Khoper, the left tributary of River Don (see Figure 2 for general location). The modern balka from the mouth to the source reaches a length of 6400 m; it has steep slopes (10–15°) and a concave longitudinal profile. Together with the branches, the balka forms a dendritic network with a total length of 11.3 km and drainage density of 0.27 km·km^{-2} (Figure 8A).
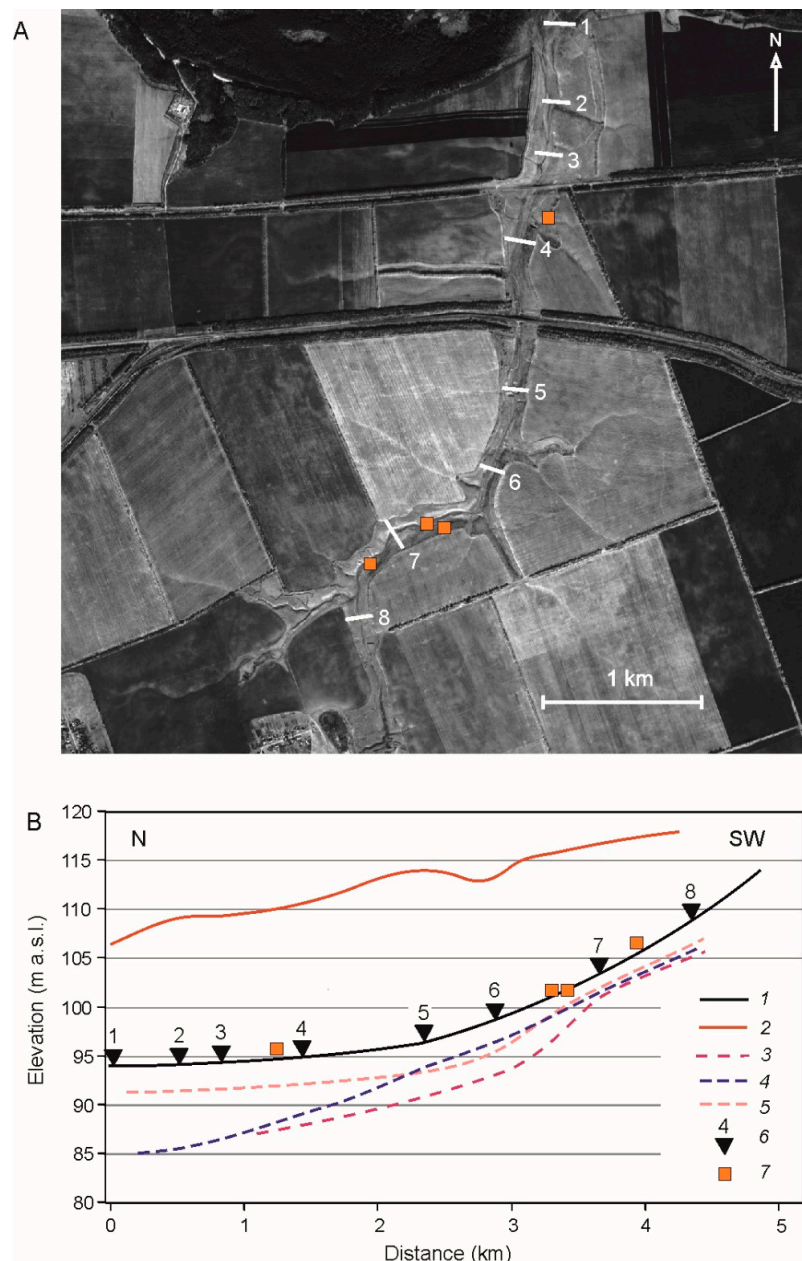
The balka depth is 10–12 m in the middle part and 12–15 m in the lower part (Figure 8B). In the upper parts of the catchment, shallow hollows continue the main balka and its tributaries. These hollows are clearly visible on satellite images by their brighter tone against the plowed fields. The heads of hollows almost reach the watershed. The length of the entire balka–hollow network is 40.5 km and its drainage density is 0.97 km·km^{-2}.

To study the sediments within the Perepolye balka, coring was performed along eight transverse profiles (Figure 9). Outcrops and pits on the steep balka sides were also investigated.
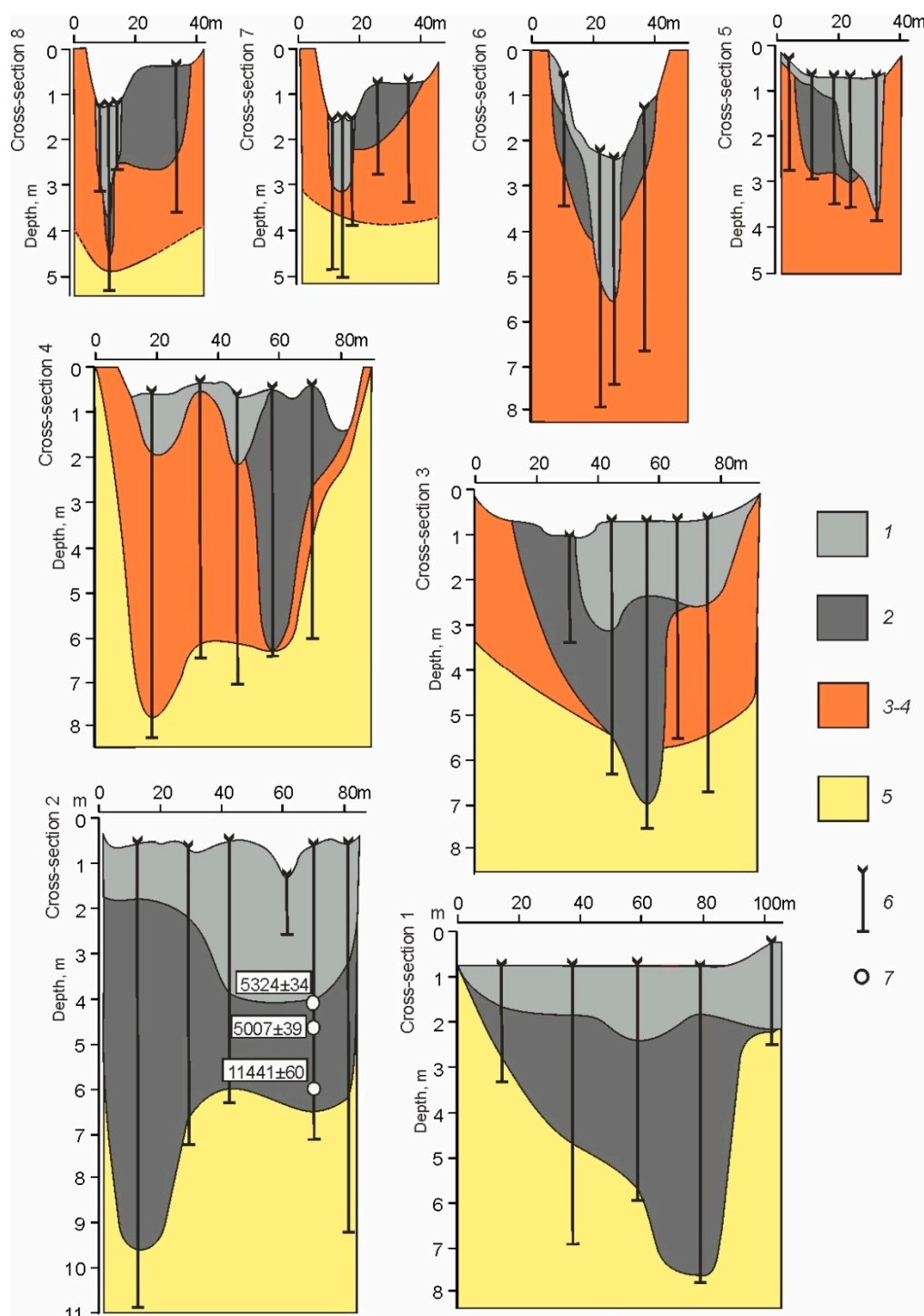
The sedimentary structures uncovered in these studies indicate the presence of three main generations of buried erosion features (Figures 10 and 11).

The first (most ancient) erosion feature is incised into the fine and medium-grained laminated alluvial sands of the third terrace of the Khoper River (Figure 10, unit 5). According to the OSL dating [39], this terrace was formed approximately 300–350 ka ago. The longitudinal profile of this erosion feature is concave (see Figure 8B). In the middle part of the Perepolye balka (Figure 9, cross-sections 4–6), this incision is much deeper than the younger ones: its thalweg is 5–7 m below the modern one. In the lower part of the balka, the first-generation incision was not traced by coring; it was possibly destroyed by subsequent erosional processes.

Near the bed of the sediments filling in the first-generation erosion feature (Figure 10, unit 4), a fossil soil with a well-defined humus horizon and numerous filled animal burrows ("krotovinas") is found (Figures 10A and 11B). This buried soil probably developed during the Last Interglacial (MIS 5e) and represents the main (Salynsk) paleosoil of the Mezin SC [31,40]. Above it, one can trace one more humus horizon of the younger Krutitsa paleosoil of the Mezin SC, tentatively correlated with the MIS 5c interstadial warming (see Figure 11B). Therefore, the incision event most probably took place at the end of MIS 6.
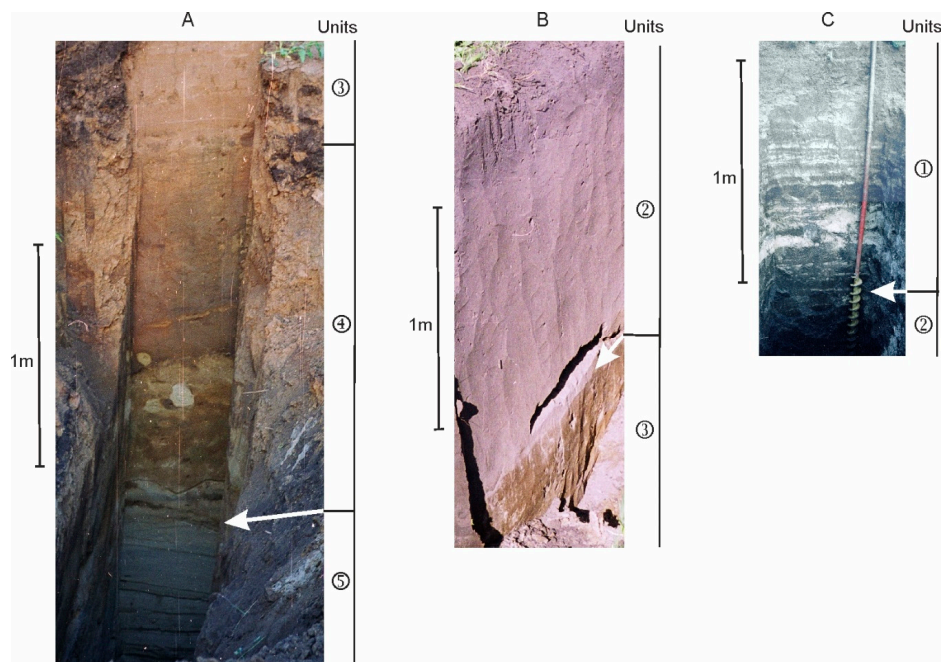

Figure 8. (**A**) Positions of cored cross-sections in Perepolye balka; (**B**) longitudinal profiles of the balka bottom (1), of the top of its slopes (2) and of the thalwegs of the buried incisions: the first generation (3), the second generation (4), the third generation (5); positions of cross-sections (6), pits and outcrops (7).
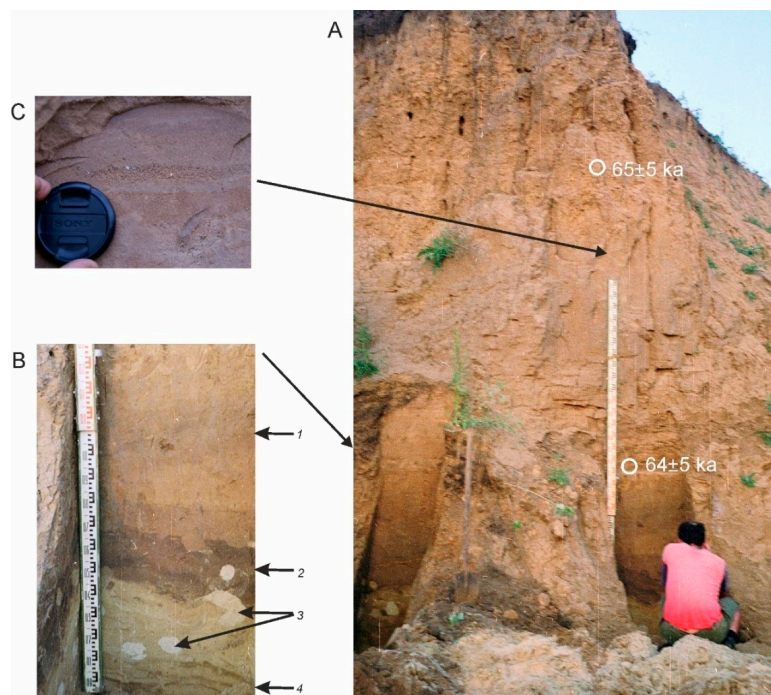
Figure 9. The composition of infill deposits at the cross-sections of Perepolye balka (see Figure 8). Keys: unit 1—the Late Holocene deposits; unit 2—the Late Glacial–Middle Holocene deposits; units 3–4—MIS 5 and MIS 4 deposits; unit 5—alluvium of the Khoper River terrace; 6—cores; 7—radiocarbon dates (uncalibrated).

Figure 10. The main layers of sediments filling in the erosion features of the first (**A**), second (**B**) and third (**C**) generations within the Perepolye balka. The numbers indicate the main lithological units discussed in the text; the arrows indicate positions of the main erosional boundaries. Photos by A. Sidorchuk.

Figure 11. (**A**) The deposits filling in an ancient erosion feature in the quarry on the slope of the Perepolye dry valley. The OSL ages of samples from sandy loams that overlay the Mezin SC are shown. (**B**) Mezin SC at the base of the MIS 6 erosion feature infill: 1—humus horizon of Krutitsa soil, 2—humus horizon of Salynsk soil, 3—krotovinas, 4—underlying alluvial sand of the Khoper River terrace. (**C**) laminated texture in sandy loam (unit 3 in Figure 10). Photos by A. Sidorchuk and A. Panin.

From a pit on the side slope of the Perepolye balka, about 4200 m from its mouth, a sample of the loam filling in the first-generation incision above the contact with the alluvial sand of the third terrace was collected (Figure 12).

Figure 12. The modern erosion cut in the bottom of Perepolye dry valley. Sampling for pollen analysis from a pit in the slope of the balka. Photo by A. Sidorchuk.

The pollen analysis of this sample performed by O. Borisova generally supported the age estimate based on the fossil soil morphology. The composition of pollen and spores indicates that, at the time of the sediment accumulation, steppe vegetation with rich variety of forbs covered the surrounding territory. Pollen of Poaceae, *Artemisia* and other plants of the Asteraceae family dominates the spectrum. Among herbaceous plants, species typical for the steppe zone such as *Echinops*, *Salvia*, *Centaurea*, and *Euphorbia* were indicated. At the bottom of the balka, with a better ground water supply, black alder (*Alnus glutinosa*) communities with minor instances of birch, linden, oak, elm and hazel were present, as well as wet meadows. Sparse *Carpinus* pollen and spores of *Osmunda* (a fern species typical of the Last Interglacial flora of the East European Plain) indicate that these relicts of the previous warm epoch persisted at the site in the most favorable locations. The presence of spores of mesophile ferns (*Botrychium*, *Ophyoglossum*) and clubmoss *Lycopodium clavatum*, with present-day ranges lying to the west and north of the Khoper River basin, suggests that the climate at the time of accumulation of the lower layers of deposits, filling in the first-generation incision, were somewhat cooler and wetter than the modern climate.

Later on, this first-generation erosion feature was filled almost to the top by the yellow-brown sandy loam deposits with a maximum thickness of over 13 m (Figures 9–11). These deposits were exposed in a small quarry on the slope of the Perepolye dry valley (Figure 11) situated between coring profiles 3 and 4 (see Figure 8A). The laminated textures of these sediments indicate their slopewash genesis. They were dated by the OSL method to approximately 65 ka ago (MIS 4) [39] (see Figure 11A,C).

We assume that the hollows in the upper parts of the balka catchment were also formed during the late MIS 6 erosion event, as they are filled in by the same kind of deposits.

The second, younger erosion feature incised into the filling of the first feature had a steeper longitudinal profile (Figure 8B). In the lower part of the balka, the loess-like deposits filling the oldest incision were completely eroded (Figure 9, cross-sections 1 and 2). In the middle part of the balka, they are preserved at the sides of the younger incisions, which are narrower than the first incision (Figure 9, cross-sections 3 and 4). In the upper part of the Perepolye balka, the second-generation incision did not reach the bottom of the first generation incision (Figure 9, cross-sections 5–8). The head of the modern balka roughly coincides with that of the second-generation incision. The network of hollows formed during the previous erosion event at the end of MIS 6 was not affected by erosion at this stage.

The second-generation incision is filled in with gray and black loams (Figure 10, unit 2 in plates B and C). These deposits form the major part of the modern balka bottom. AMS radiocarbon dating (Table 1) showed that the age of black heavy loams near the base of the layer is 11,441 ± 60 ^{14}C yr BP (AA104015) (Figure 9, cross-section 2). This agrees well with the date 11,900 ± 120 (Ki-5305) obtained for the deposits filling a similar incision in the nearby Khoprets balka [41] (see Figure 7 for the position). These dates, along with the reconstructions of the history of the Khoper River channel evolution [41,42], suggest that the second-generation erosional feature was formed soon after the Last Glacial Maximum, in the Late Pleniglacial. It started to fill at the Late Glacial. According to the radiocarbon dating (Table 1), deposition in the second-generation erosion feature continued at least until the middle of the Holocene.

Table 1. Radiocarbon dates from cross-section 2 in the Perepolye balka (see Figure 9).

Laboratory Code	Sample Depth (cm)	dC13 in Graphite, ‰	^{14}C Age BP	Calibrated Age, cal BP *
AA104012	360–370	−26.8	5325 ± 35	6100 ± 70
AA104013	390–400	−29.2	5010 ± 40	5760 ± 80
AA104014	510–520	−29.7	11,440 ± 60	13,310 ± 70

* OxCal 4.3.2, IntCal20.

The climatic conditions at the time when the second-generation incision began to fill with sediments were reconstructed from palynological data by analyzing the modern ranges of species that make up the fossil flora of a dated loam sample. A region-analogue for this fossil flora lies at the Southern Ural Mountains, between the headwaters of the Ufa and Ai Rivers. In this region, southern Urals birch and pine forests come into close contact with meadow steppes [43]. This area is characterized by relatively cool climatic conditions: the mean January air temperature there is −15.5 °C (which is 8 °C lower than the modern temperature in the Perepolye balka region), and the mean July temperature is about 17.5 °C (5 °C lower than the modern summer temperature). The mean annual precipitation within the region-analogue is 600–650 mm. This exceeds the modern value at the site by 150 mm. The annual runoff depth in the region-analogue is about 170–200 mm, while in the study area, at present it is only 100 mm. Based on the obtained reconstruction, we explain the considerable increase in runoff not only by the greater amount of precipitation in the Late Glacial but also by significantly lower temperatures, especially in winter. The reconstructed climatic values refer to the initial stage of the second-generation incision filling. At the stage of incision at the Late Pleniglacial, the annual runoff (and its irregularity during the year) was even higher and reached 330 mm, as estimated from the structure of erosion relief [44].

The third-generation incision, which was probably formed during the Late Holocene, has a longitudinal profile that is similar in shape to the modern one (line 3 in Figure 8B), a depth of about 3 m and a relatively small width in the upper part of the balka (10–15 m) increasing to 30–40 m in its middle part (see Figure 9). In the upper part of the balka, the third-generation incision is filled with alternating interlayers of light-gray sand (unit 1 in Figure 10) and dark gray or black loam. The sand came from
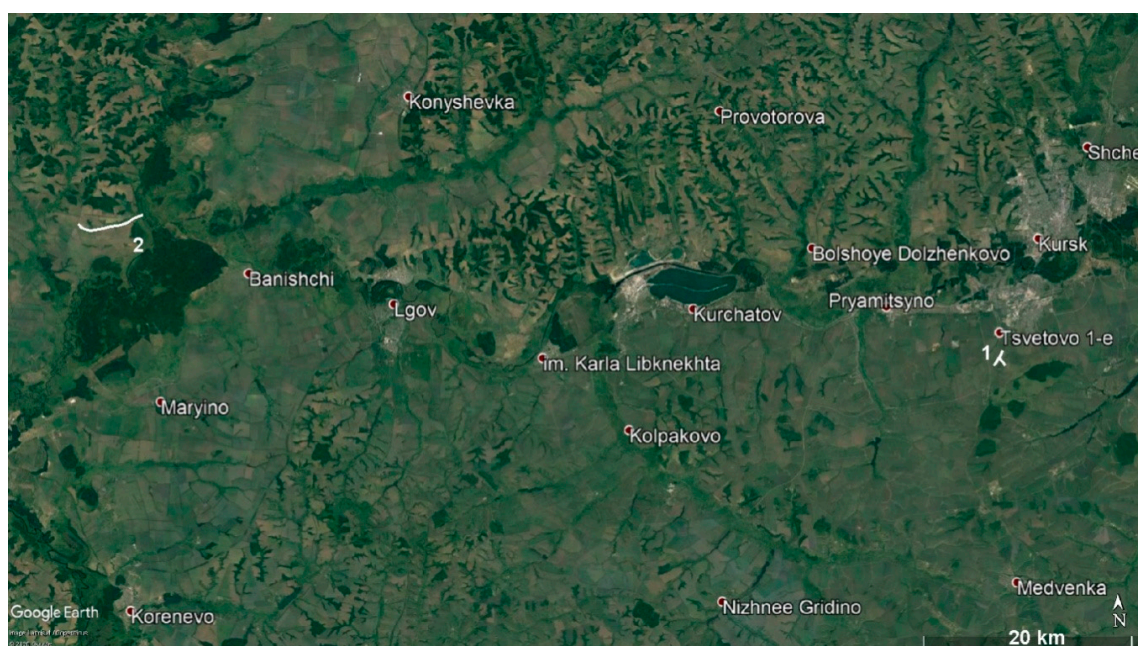
the erosion of the Khoper River terrace alluvium (unit 5 in Figure 10), and the source of the loam was the filling of the previous incision (unit 3–4 in Figures 9 and 10) and/or the Holocene Chernozem soil from the balka slopes. In the lowermost part of the balka, an incision of the third generation is not traced. Probably, mainly sediment accumulation took place there (see Figure 9, cross-sections 1). The entire width of the dry valley bottom near its mouth is covered with brown loam which is 1–3 m thick (unit 1 in Figure 9).

In the bottom of the Perepolye balka, there is also a modern incision up to 1 m deep, which can be seen in Figure 12.

Two main deep incisions of the first and second generations at the ends of MIS 6 and MIS 2 glaciations were caused by high surface runoff. The annual values were estimated from the values of drainage density, with the help of analogs from modern Arctic regions, as 600–1000 mm for the end of MIS 6 and 330 mm for the end of MIS 2 [44]. The most intensive deposition of sediments from the slopes within the catchment took place during the cold MIS 4 epoch and in the Late Glacial period. The Last Interglacial and the Holocene were the epochs of the reduction of erosion/deposition processes, landscape stabilization and the formation of soil cover in erosion forms, with some activation of erosion processes during cooler and wetter stages; for example, in the late Holocene.

3.3. The Seim River Basin

The southern side of the Seim River basin is dissected by balka networks with a general drainage density of 0.8 km·km^{-2} (Figure 13). Many balkas in the region almost reach watersheds, meaning that the hollows in their upper reaches are largely destroyed by subsequent erosion.

Figure 13. Balka-hollow network in the Seim River basin. 1—Kukuyevsky Log balka, 2—Kramskoy Log balka.

Kukuyevsky Log balka has a catchment area of 7.3 km^2 and a length of 3.9 km. It continues towards the watershed with shallow hollows. A so-called Aleksandrovsky loam quarry exposes the deposits filling in one of these hollows (Figure 14).
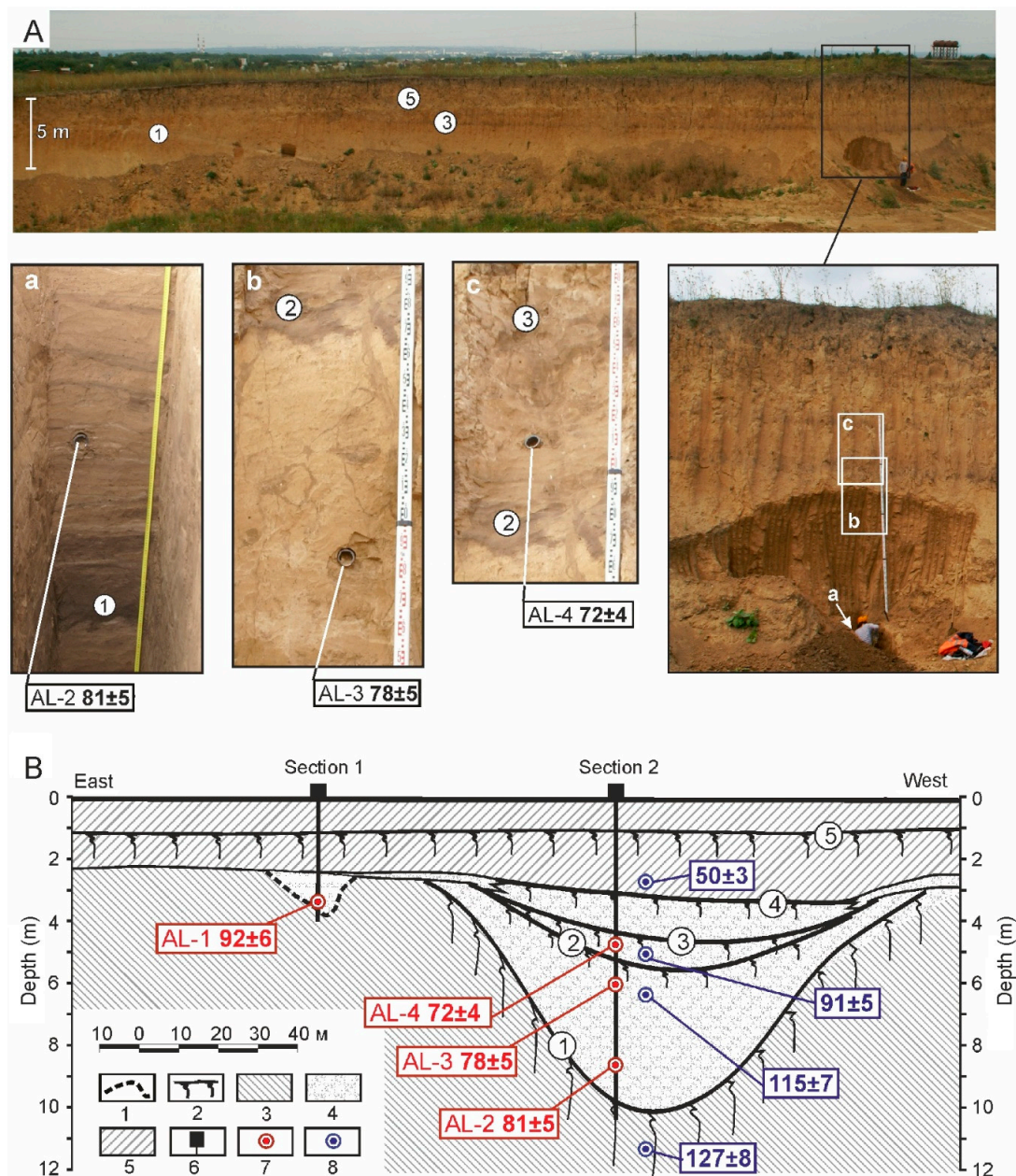
Figure 14. Kukuyevsky Log balka system (solid lines) with the buried hollow (dashed line) exposed in the Aleksandrovsky loam quarry in 2009 (dotted outlines). Black dots and numbers are the studied geological sections (see Figure 15).

The texture of these deposits reveals an ancient dry valley (balka) completely buried by subsequent sedimentation. Well-defined paleosoil horizons mark the end of each sediment series. This incision was formed before the formation of Mezin SC, as its slopes and bottom are covered by a well-developed soil, which is correlated with the Salynsk phase of Mezin SC [45–47], corresponding to the Last Interglacial (MIS 5e). The cross-section shape of the ancient balka is asymmetric. Its short left side is convex and steep (about 15°), while the opposite slope is longer, straighter and more gentle (about 8°). The total width of the erosion feature is 90 m; its maximum depth is about 7–8 m.

The ancient balka is filled with slopewash and solifluction loams [48]. The presence of cryogenic deformations indicates that they developed in a periglacial setting. An additional "trigger" that contributed to the sediment mobilization from the slopes was provided by fires, indicated by the abundant charcoal fragments found in the sedimentary fill. Episodes of rapid sedimentation were followed by phases of stabilization of the sides and bottom of the balka. Four paleosoils—Kukuyevo, Streletsk, Aleksandrovsk (local terms suggested by Sycheva [45,49] and Bryansk paleosoil—are found above the main Salynsk paleosoil of the Mezin SC. The main deposition phase took place between the formation of the Salynsk and Kukuyevo paleosoils. The erosion feature outlined by the Aleksandrovsk paleosoil was already a gentle hollow (this paleosoil is not detected in the quarry wall shown in Figure 15). The Bryansk paleosoil distinguished below the Holocene Chernozem lies sub-horizontally over both the ancient erosion features and interfluves. The positions and morphology of the buried erosion features and fossil soils, exposed in the quarry wall in 1986 [45], have been changing as the wall retreated during the quarry exploitation [46–48].

Figure 15. Buried balka in the Aleksandrovsky quarry. (**A**) The wall sampled in 2009 (view from south to north) and sections a, b and c with different paleosoils on this wall. Photo by A. Panin. Paleosoils: ①—Salynsk, ②—Kukuyevo, ③—Streletsk, ⑤—Bryansk. Aleksandrovsk paleosoil (No. 4) was not detected in the quarry wall at this time. (**B**) Summary section of buried balka based on [48], view from north to south. 1—buried erosion forms; 2—paleosoils: ①—Salynsk, ②—Kukuyevo, ③—Streletsk, ④—Aleksandrovsk, ⑤—Bryansk; 3—MIS 6 loess; 4—infillings of buried erosion forms; 5—MIS 3—MIS 2 loess; 6—generalized position of sections studied in 2009; 7—OSL dates reported in [37] and discussed for the first time in this study; 8—IRSL (Infrared Stimulated Luminescence) dates (fading uncorrected) reported in [49].

To establish the chronology of incision/aggradation events and the phases of soil formation in the buried balka, we took four samples for OSL dating (Figure 15). These samples were dated at The Nordic Laboratory for Luminescence Dating (Aarhus University, Aarhus, Denmark) (Table 2).

Table 2. OSL ages of deposits filling the ancient balka system in the Aleksandrovsky quarry (see Figure 15), after [37] with correction.

Date, ka	Laboratory Number (Risø)	Sample Characteristics			Laboratory Data for Age Calculation			
		Field Code	$H_{a.s.l.}$	D, m	WC, %	n	ED, Gy	DR, Gy ka^{-1}
92 ± 6	106108	AL-1	250	3.5	24	29	263 ± 11	2.85 ± 0.11
81 ± 5	106116	AL-2	241	7.3	21	18	233 ± 9	2.88 ± 0.12
78 ± 5	106129	AL-3	244	4.2	22	23	217 ± 9	2.79 ± 0.11
72 ± 4 *	106123	AL-4	245.5	2.9	22	32	198 ± 6	2.76 ± 0.09

* Corrected compared to published in [37] (see explanations in the text). $H_{a.s.l.}$—elevation above sea level; D—sample depth; WC—mean water content in the sample over the entire burial period; n—number of aliquots; ED—equivalent dose; DR—dose rate.

Samples 2–4 were taken from the same section and characterized by their similar mechanical composition and water content. The date for sample AL-4 was initially calculated with an improbably high mean water content (WC) value of 38%, which led to the significant overestimation of the age published in [37]. Here, we provide the corrected date of 72 ± 4 ka recalculated with a WC of 22%, which is characteristic of the other three samples.

Sample AL-1 refers to a minor erosion event on slopes that occurred during the likely stabilization phase of the development of the balka. Samples AL-2 and AL-3 characterize the main stage of the ancient balka filling, separating the formation of the Salynsk and Kukuyevo paleosoils. Sample AL-2, collected 40 cm above the top of the Salynsk soil, indicates the beginning of the filling process at 81 ± 5 ka. Sample AL-3, collected 100 cm below the top of the Kukuyevo paleosoil, corresponds to the end of the major filling phase at 78 ± 5 ka. Sample AL-4 (72 ± 4 ka) characterizes the second, minor phase of filling, when the sediments separating the Kukuyevo and Streletsk paleosoils were formed; the depth range between the tops of these soils is 0.8 m (Figure 15).

The dating results show that the sedimentary filling of the main erosion form took place at the end of MIS 5 and was quite rapid. The erosion feature was completely filled by MIS 3, and Bryansk soil was formed on top of these sediments. The later erosion events, which presumably formed the dry valley at the lower part of the catchment, did not affect this buried feature. A surprisingly long break of about 30–40 thousand years occurred between the formation of the Salynsk paleosoil at the balka bottom by the end of the Eemian Interglacial (~115 ka) and the start of sedimentation and soil burial. The balka bottom must have been relatively stable during this entire period, as follows from the general preservation of the Salynsk paleosoil, both on the sides and the bottom of the balka.
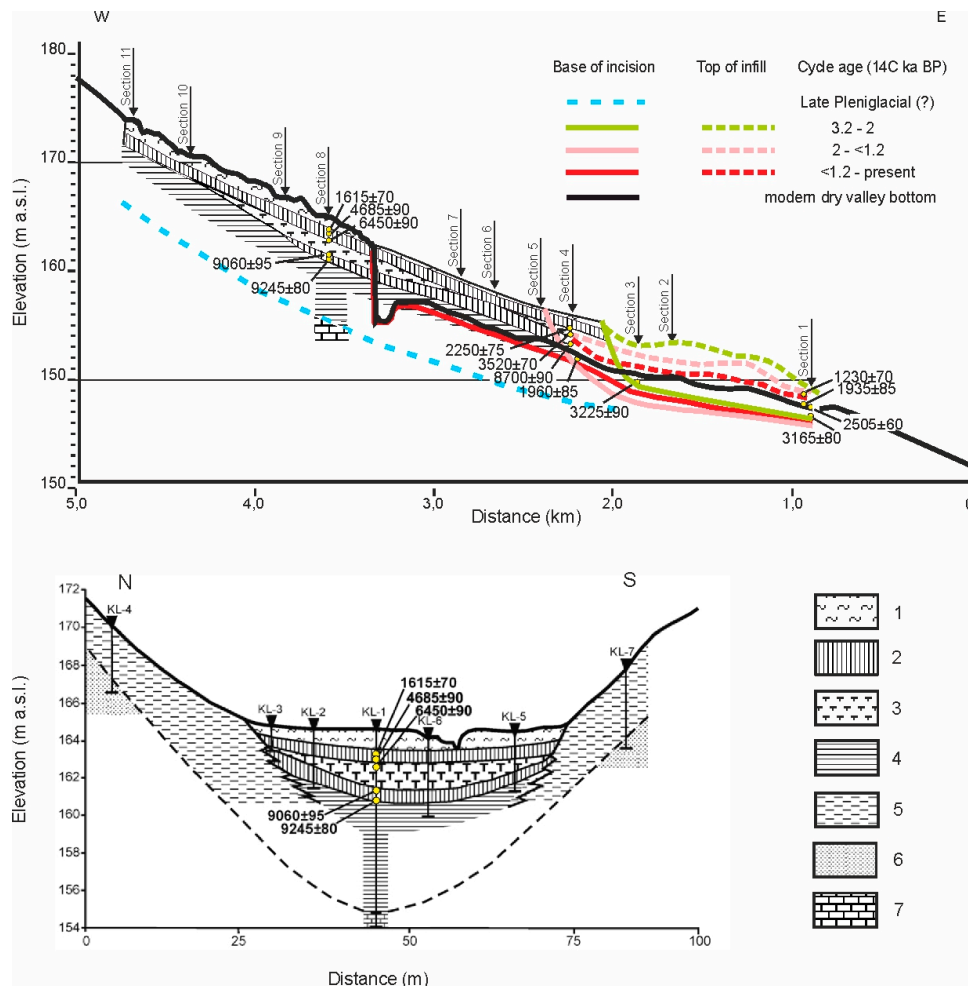
Recently, Sycheva et al. [49] reported four more luminescence (IRSL) dates from the wall of the Aleksandrovsky quarry (generalized positions of the samples is shown in Figure 15B). IRSL dating was performed at the Leibniz Institute for Applied Geophysics, Hanover, Germany. The dates obtained by Sycheva et al. [49] from the infill of buried balka were systematically older than the dates reported in this study (see Figure 15B). The main cause for this could be the difference in the methods used in these two laboratories and different minerals taken for dating. Presumably, some IRSL dates reported in [49] are systematically older than those in Table 2 due to the much longer time needed for the zeroing of feldspars compared to the quartz used in OSL dating. However, according to both groups of dates, the three lower meters of the sedimentary fill in the main erosion feature were deposited quite rapidly. In any case, to construct a convincing geochronological model for the development of the balka exposed in the Aleksandrovsky quarry, a more robust series of dates is required.

As the erosion history in the Late Glacial and the Holocene was not represented by the Kukuevsky Log case study, we investigated yet another balka in the Seim River basin: the Kramskoy Log (Figure 16; see Figure 13 for location). The composition of deposits filling the balka bottom was studied in 11 cross-sections based on coring data and DGPS topographic survey (Figure 17).
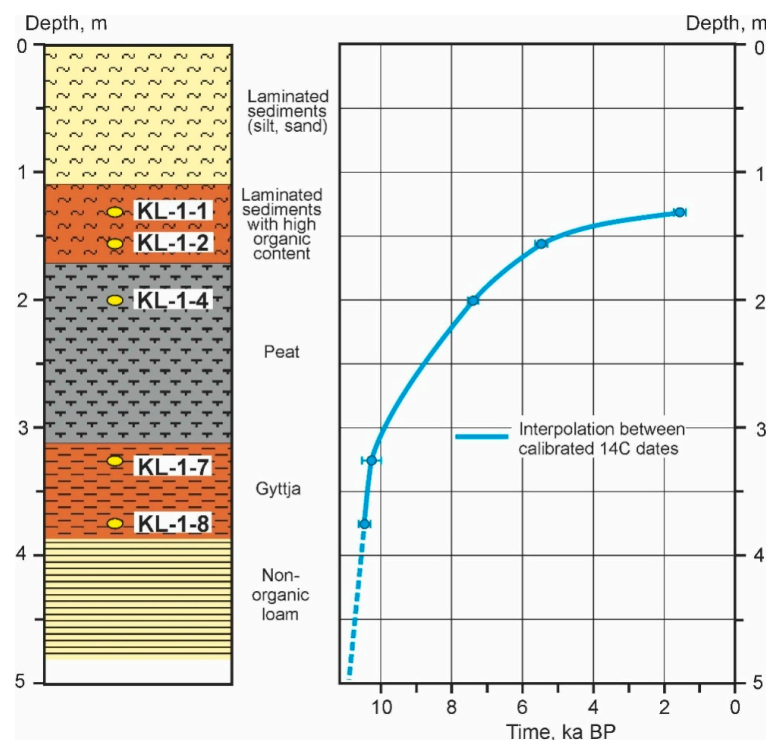
Figure 16. Kramskoy Log balka.

Figure 17. Composition of the sedimentary fill of the Kramskoy Log balka. Upper plate—Longitudinal profile and erosion-deposition rhythms from the second half of the Holocene. Lower plate—geological cross-section 8 with ^{14}C dates (uncalibrated). Legend: 1—laminated sandy loam and sand, 2—loam rich in organic matter, 3—peat, 4—loam poor in organic matter, 5—loam, 6—Paleogene sand, 7—Cretaceous chalk and marl.

In the middle part of the balka, the base of the sedimentary fill was found by coring at a depth of about 10 m (Figure 17). Radiocarbon dating in combination with the correlation of erosion terraces in the bottom gully in the balka lower reach allowed the reconstruction of the main incision–deposition rhythms that occurred in the balka since the Late Glacial period.

The lower six meters of the infilling deposits are bluish heavy loams that contain virtually no organic matter. After the onset of the Holocene (^{14}C date 9245 ± 80 in Table 3), the sedimentary fill changed into a dark grey loam rich in organic matter. The half-meter thick layer between the two lowermost samples accumulated, very roughly, over 200 years, which results in an accumulation rate of about 25 cm/100 years (Figure 18). The extrapolation of this accumulation rate to the undated six-meter lowermost layer of bluish non-organic loam gives a deposition time of about 2.5 ka. This very rough estimate gives only an order of magnitude. Nevertheless, it is clear that at the end of the Late Glacial—probably during the Younger Dryas—the rapid filling of the balka had already begun. Regarding the deepest incision, its age remains unclear, but by analogy with the other studied regions, it can be assumed that it formed during the period from the Late Pleniglacial to the first half of the Late Glacial.

Table 3. Radiocarbon dates from cross-section 8 in Kramskoy Log balka (after [50]).

Laboratory Code	Field Code	Sample Depth (cm)	^{14}C Age BP (yr)	Calibrated Age, cal BP (OxCal 4.3.2, IntCal20)
Ki-7197	KL-1-8	3.75	9245 ± 70	10,420 ± 100
Ki-7196	KL-1-7	3.25	9060 ± 95	10,210 ± 150
Ki-7195	KL-1-4	2.0	6450 ± 90	7360 ± 90
Ki-7194	KL-1-2	1.55	4685 ± 90	5410 ± 120
Ki-7193	KL-1-1	1.30	1615 ± 70	1500 ± 80

Figure 18. Changes of sedimentation rates in the middle part of Kramskoy Log balka in the Holocene. Sample codes in the lithological column correspond to Table 3.

About 10,000 years ago, a swamp formed in the bottom of the balka, and peat began to accumulate at an average rate of 4.5 cm/100 years (Figure 18). Taking into account the date of the peat top (calibrated ^{14}C date 7360 ± 90) and the probable erosion of the 0.5 m top layer, the end of organic matter accumulation can be estimated at about 6 ka. Later on, peat accumulation was succeeded by the deposition of organic-rich mineral sediments. A 70 cm thick layer formed over nearly 6000 years, with a sedimentation rate of 1.2 cm per 100 years. The bottom of the balka in the middle part practically stabilized. However, in the lower reaches of the balka, the sequential development of bottom gullies began in that period. The headwater erosion of each subsequent gully moved farther upstream, and due to the re-deposition of sediments mobilized by headcut erosion, a series of terraces formed in the lower part of the balka that can be well distinguished on the cross-sections surveyed in the field. The ^{14}C dating of the sediments composing these terraces made it possible to estimate the time boundaries of three erosion-accumulation cycles: 3.2–2 ka, 2–1.2 ka and <1.2 ka ^{14}C BP–present (Figure 17). The last development phase of the modern linear erosion in the balka bottom coincides with the beginning of agricultural development of the balka catchment.

Similar Holocene fillings of preceding incisions were uncovered by coring in the Berestovaya [51] and Kazgulak balkas [23,30] (see Figure 2 for locations).
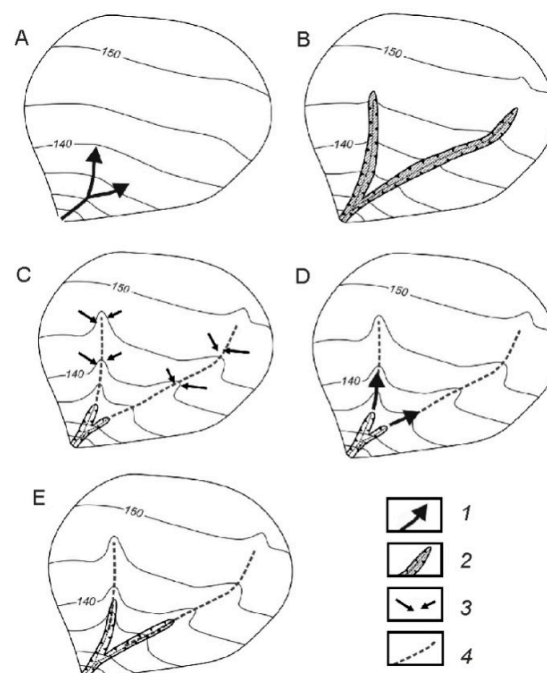
4. Discussion

There are three main questions to discuss based on the data from the upper reaches of the fluvial systems on the East European Plain: (1) the sequence of erosion and deposition events, (2) the causes and chronology of the incision/aggradation rhythms and (3) the influence of these events on landscapes and sedimentary archives.

4.1. Sequence of Erosion and Accumulation Events

The balka-hollow topography in the extraglacial regions of the East European Plain is morphologically diverse and includes erosion features that formed at different stages of the development of the terrain [52]. The presented results and analysis of literature sources [21,30,50] allow us to conclude that balkas and hollows in the upper reaches of fluvial systems were originally formed as deep gully-like incisions, mostly in the late MIS 6 period (Figure 19A). In many cases, they may have inherited the ancient erosion network mainly buried by loess and slopewash sedimentation during the preceding glacial epoch. These gullies dissected the river basins nearly up to the water divides. The partial infilling of these gullies, their stabilization and gradual transformation into balkas began at the MIS 6–MIS 5 transition and continued into MIS 5e, when organic-rich Salynsk soil of Mezin SC formed at the bottoms of balkas (Figure 19B).

The main stage of the filling of erosion incisions by slopewash deposits and then by loess occurred in the later part of MIS 5 and in MIS 4 (Figure 19C). This deposition was discontinuous and was repeatedly interrupted by episodes of soil formation (Figure 15B). A minor erosion phase in balkas (traces of linear erosion in bottoms) was detected from the textures of filling deposits in late MIS 5e–MIS 5d [48]. Furthermore, the development of erosion rills on watersheds occurred at around 90 ka (see results from Kukuyevsky Log in Section 3.2). Nevertheless, these erosion episodes were second-order events compared to the general trends of balka stabilization and subsequent filling by slope deposits. The result of this prevailing deposition was the nearly complete planation of the terrain and the transformation of MIS 6 gullies into shallow hollows by the end of MIS 4.

Figure 19. Development of the upper reaches of fluvial systems during the last two glacial-interglacial cycles: (**A**)—the end of the Penultimate Glaciation (MIS 6); (**B**)—the Last Interglacial (MIS 5e, 130–115 ka ago); (**C**)—Early Glacial—Last Glacial Maximum (115–18 ka ago); (**D**)—the Late Pleniglacial and the Late Glacial (18–13 ka ago); (**E**)—the end of Late Glacial and the Holocene (13 ka—present). Keys: 1—headcut growth of gullies; 2—edges of balkas; 3—filling of gullies with products of slopewash; 4—thalwegs of hollows.

The composition of the Kukuyevsky Log balka in the Aleksandrovsky quarry (Section 3.2) gives us the impression that the drainage system remained relatively stable during MIS 3 and the early part of MIS 2, as indicated by the Bryansk soil (MIS 3), which covers the bottoms and slopes of buried hollows, as well as the interfluves (Figure 15B). However, this interpretation may be incomplete. For example, in Pokrovsky Log balka (site 11 in Figure 2), the incision phase occurred in the late MIS 3 [53], which is similar to the incision phase in the Seim River valley [18]. Therefore, the spatial coverage and magnitude of the MIS 3 incision phase in the upper reaches of fluvial systems remains a challenge for future research.

The last widespread erosion event took place in the Late Pleniglacial (after ca. 18 ka), according to our investigations, in the river valleys in the extraglacial region [54–56]. This phase was detected in all our case studies (Figure 19D). The gully-like incisions mostly inherited the hollows of the MIS 6 erosion event and were as deep as the previous incisions but were not as long, reaching only about half or two-thirds of their length. The infill of these gullies and their transformation into the modern balkas started in the late Late Glacial period (12–13 ka BP) and continued into the Holocene, when products of soil and gully erosion were trapped in balka bottoms and formed a clearly distinguishable organic-rich sedimentary body. This deposition occurred mostly in the Early-Middle Holocene (Figures 18 and 19E). After ca. 5 ka BP, balkas almost stabilized or even switched to a minor incision phase, which resulted in the repeated development of bottom gullies (Figure 17) due to an increase in precipitation in the Late Holocene. Incisions of the same age were also detected in the fluvial net headwaters in the western part of the East European Plain [57] and as far as the Pyrenees [58].
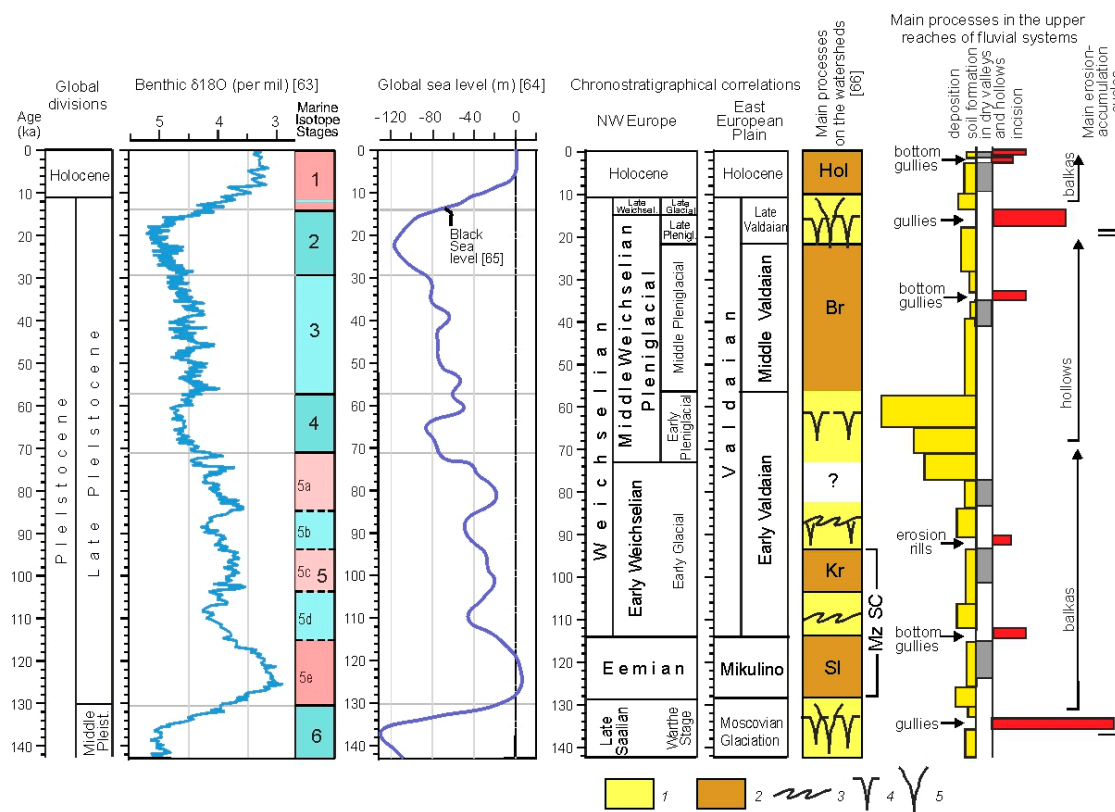
In some balkas in the very south of the region, such as the Berestovaya balka [52] and Kazgulak balka [23] (see location in Figure 2), the formation of bottom gullies started only in the middle of the last millennium, which was possibly due to an increase in runoff during the Little Ice Age. They were definitely not related to agricultural activity, as both areas were only ploughed in the 20th century.

To date, we do not have data on cycles earlier than MIS 6 of erosion–accumulation in the upper reaches of the fluvial systems on the East European Plain, although such cycles are well known in the river valleys [12–14,59–62].

4.2. The Causes of the Alternation of Erosion and Accumulation Phases

Based on the chronological and stratigraphic materials discussed above, we conclude that the distinguished incision–aggradation rhythms generally correspond to the global glacial–interglacial cycle (Figure 20). The structure of this cycle is most clearly reflected in the oceanic oxygen-isotope curve derived from benthic foraminifera [63], as well as in the global sea level changes [64].

Two main incision phases in late MIS 6 and late MIS 2 occurred during the low stands of the World Ocean. The lowering of the global base level could not directly influence the erosion activity in areas deep in the continental interior, such as the Seim, upper Don and Khoper river basins, but may have influenced the development of the erosion network in coastal areas such as the Azov Sea coast (Figure 2). During the last and penultimate glacial ages, the Azov Sea did not exist. The Black Sea level during the Late Pleniglacial was at approximately −62 to −67 m [65].

Figure 20. Correlation of chronostratigraphic subdivision and environmental processes for the last 140,000 years: marine isotope stages (data from [63])–global sea level (data from [64])–Black Sea level (data from [65])–chronostratigraphic correlation of north-west Europe and East European Plain–the main processes on the watersheds and in the upper reaches of fluvial systems. Keys: 1—predominant loess accumulation on the watersheds; 2—predominant soil formation (Sl—Salynsk soil and Kr—Krutitsa soil of the Mezin soil complex, Mz SC, Br—Bryansk soil, Hol—Holocene soil); 3–5—typical permafrost features (3—involutions, 4—small ice-wedge casts, 5—large ice-wedge casts) (data from [66]).

The River Don flowed through what would become the Taganrog Bay, then through what is now the bottom of the Azov Sea and reached the Black Sea south from the present-day Kerch Straight, more than 300 km from the present-day Don River mouth in the Taganrog Bay. This elongation of the river could compensate for the base level decrease in terms of changing the river slope and preventing

river incision, as shown in [1]. The modern example is River Volga, which did not incise during the drop of the Caspian Sea level in the mid-20th century [67].

Nevertheless, coring in the lower Don valley showed that the river was incised below the present sea level by more than 10 m in MIS 2 and up to 20–25 m in MIS 6 [68]. There were also phases of the incision of dry valleys in the Azov region at the end of MIS 6 and at the end of MIS 2. The problem is that the bottoms of incisions are not at the base level of that time but at higher altitudes. This question needs further investigation. One of the explanations is that the high cliffs of the Azov Sea coast now retreat with a high rate of several meters a year [69]; therefore, the now hanging mouths of buried balkas may have been located at their middle reaches at the periods of the low stand of the base-level and therefore at higher altitudes.
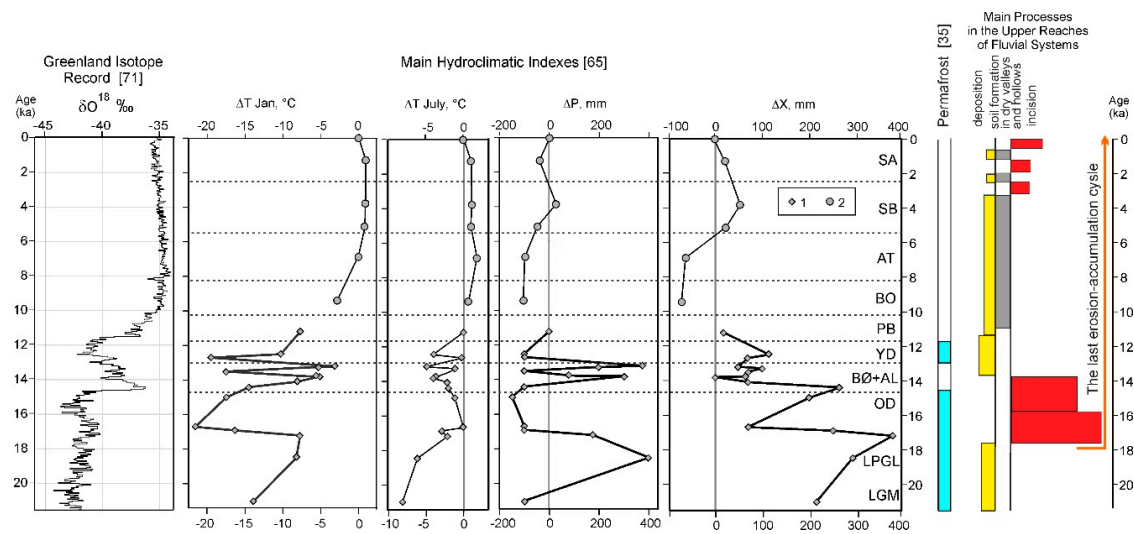
Taking into account the local features of the geological structure and topography of the territory, the evolution of the upper reaches of fluvial systems in the extraglacial part of the East European Plain was governed by changes in surface runoff and protective properties of vegetation cover. These two main factors in turn depended primarily on the heat and moisture supply. Both characteristics change quasi-periodically over time, with different periods and amplitudes. The phases of the oscillations of heat and moisture usually do not coincide. Surface runoff is a nonlinear function of the combination of moisture and heat availability. Therefore, its changes over time often weakly correlate with changes in these separate climatic characteristics. The vegetation cover had a more complex reaction to climate change, possessing the ability to self-regulate, adapt and regenerate.

This complex sequence of amplitudes and trends in climatic characteristics resulted in a complex multi-level evolution of the fluvial systems. In this evolution, the main quasiperiodic changes—glacial–interglacial cycles—are quite clearly distinguished. These cycles are characterized by the largest amplitude of change in the erosional topography and in the intensity of the processes of erosion and sedimentation. Due to a complex interaction between the main factors, the extremes of erosion and deposition in the upper reaches of the fluvial systems do not coincide with the extremes of temperature and humidity.

At present, two major phases of incision were reconstructed by our investigation in the extraglacial part of the East European Plain: the first of them occurred in the post-maximum part of MIS 6, starting from about 140 ka ago, while the last one occurred in the Late Pleniglacial, from 18 to ca. 13 ka ago (Figure 20). It is possible that similar erosion events also occurred in the periglacial zone at the ends of earlier glaciations. Events of this rank for earlier glaciations have been revealed in river valleys of different regions [59–62]; however, there are still no convincing data for the upper links of erosion networks. To the west of East European Plain, ancient (Elsterian) erosion features are also presumed but have not been proven [70].

Each incision–aggradation rhythm contains the same major events caused by similar hydro-climatic and landscape conditions (Figure 20). These conditions are better known for the last glacial–interglacial cycle (Figure 21), for which quantitative estimates are available [65]. At the beginning of this major cycle at the end of glaciation, a deep incision of the entire fluvial system, from erosional furrows on slopes and in gullies to river channels, was the result of large surface runoff during the period of snow melting after a long cold winter. This sharp increase in runoff was caused by a slight increase in precipitation—mainly in winter—low evaporation and infiltration losses due to still low temperatures and the presence of permafrost and sparse vegetation. At the end of this phase, the erosion network and river channels were partially filled with sediments.

The stabilization of all elements of the erosional relief and the reduction to a minimum of the intensity of both erosion and deposition processes are associated with the establishment of interglacial conditions with a warm and humid climate, dense vegetation and much lower and uniform surface runoff, due to higher losses to evaporation and infiltration.

Figure 21. Reconstruction of the main climatic indexes, runoff changes and predominant processes in the upper reaches of fluvial systems in the southern East European Plain for the last 22 ka compared to NorthGRIP oxygen isotope record (data from [71]) and European climatostratigraphic scale. LGM—Last Glacial Maximum; LPGL—Late Pleniglacial; Late Glacial: OD—Oldest Dryas, BØ+AL—Bølling-Allerød interstadial including a short cooling of the Older Dryas, YD—Younger Dryas; the Holocene: PB—Preboreal, BO—Boreal, AT—Atlantic, SB—Subboreal, SA—Subatlantic. Keys: 1—reconstructions of the Late Pleniglacial and Late Glacial [72,73], 2—reconstructions of the Holocene [74].

The smoothing and disappearing of the erosional relief, the planation of erosional forms on interfluves due to areal sedimentary deposition, the filling of gully–balka systems with colluvial sediments and the reduction to a minimum of the intensity of fluvial morphogenesis were associated with conditions of subsequent glaciation, with a cold and dry climate, sparse vegetation and minimal surface runoff, widespread development of permafrost with cryogenic slope processes, aeolian transport and loess formation.

After the next glacial maximum, a new phase of deep incision and the maximum intensity of fluvial processes began the next large cycle of fluvial system evolution.

Against the background of a large global cycle of the evolution of fluvial systems, quasiperiodic changes in the morphology of the erosion–deposition complex associated with climatic variations of the second order were also revealed, with a period of several thousand years or less. The characteristics of these oscillations can vary greatly depending on the ratio of heat and moisture and their trends. The reaction of the upper reaches of fluvial systems to these changes can also be very different. The existing data show a relative increase of erosion during the cooler and wetter climatic episodes.

4.3. Influence of Erosion–Deposition Rhythms on Landscape Morphology and Sedimentary Archives

The phases of maximum surface runoff and the intensive incision of gullies in river basins of extraglacial regions of the East European Plain were the periods of formation of the recent fluvial relief. The mean annual surface runoff during this phase at the end of MIS 2, 18–13 ka ago, was two to three times that of the modern runoff, and the annual maximum was five to six times greater than the modern maximum [55,75]. The dense network of recent balkas was formed by this high runoff. These balkas are the most pronounced element of the modern erosional landscape. The calculations for the Don River basin [76] produced some numerical estimates of this event. About 44,500 balkas of 1–10 km in length, with a total length of 222,700 km, formed within an area of 425,000 km^2. The mean depth of those gullies at that time was about 22 m, and their total volume that equaled the volume of mobilized sediments was about 290 km^3. The maximum annual rate of erosion was about 340 m^3/km^2.

As river channels of this period were also deeply incised, all of this sediment was delivered to the Black Sea, where a distinct maximum of the deposition rate is detected for this period [77]. The subsequent sediment accumulation in balka network during the Late Glacial and the Holocene periods amounted for about 60 km^3 with an annual rate of about 10 m^3/km^2 [76].

The erosion event at the end of MIS 6 was much more significant than the subsequent event. It was estimated for the Khoper River Basin that the average annual surface runoff at that time was at least six times higher than today [78]. As a result, a dense network of gullies was formed. The total drainage density of modern balkas and hollows, which at the time of this event were deep gullies, was 5–6 times greater than the density of the network of modern balkas in the south of the East European Plain and about 20–30% greater than in the northern part of the extraglacial region of the plain. The subsequent sedimentation, which lasted over 100,000 years, was large enough to fill these gully incisions almost completely, turning them first into balkas and then into hollows. The main geological contribution of this incision–aggradation rhythm was the formation of sediment strata that almost completely filled the ancient erosion network, while its manifestation in the modern topography of the region is limited to a network of shallow hollows in catchments in the upper reaches of the fluvial network.

5. Conclusions

The main phases of the development of the upper reaches of fluvial systems in the extraglacial region of the East European Plain against the background of the glacial–interglacial climatic cycles have been established.

(1) There was the phase of high surface runoff and activation of linear erosion during the end of glaciation with a cool and wet climate, with permafrost and sparse vegetation, the result of which was the formation of the dense gully network;

(2) the phase of rapid partial filling of erosion formed at the glacial–interglacial transition and early interglacial period, with the subsequent stabilization of erosion landscapes during the rest of the warm and humid interglacial period with dense vegetation, resulting in the transformation of gullies into balkas (dry valleys) and in regional soil formation at their bottoms;

(3) the phase of long-term steady sediment deposition in the balka network by slope and aeolian processes during the cold and dry part of the glacial epoch, resulting in the transformation of balkas into shallow hollows;

(4) second-order phases of erosion activity occurred in the warmer intervals of the glacial part of the climate cycle and in cooler/wetter intervals of the interglacial part.

The main influence of the erosion–accumulation cycle that started in the late MIS 6 was the formation of sediment strata that almost completely filled the ancient erosion network, while its manifestation in the modern topography of the region is limited to a network of shallow hollows over watersheds in the upper reaches of fluvial network. The last (incomplete) incision–aggradation rhythm beginning at the late MIS 2 caused the formation of the modern erosion landscape. It has now reached the stabilization phase. The main aggradation phase of this rhythm has not yet taken place.

References

1.　Makkaveev, N.I. *The River Channel and Erosion in its Basin (Ruslo Reki i Erosiya v Eye Basseine)*; Akademizdat: Moscow, Russia, 1955; p. 346. (In Russian)

2.　Schumm, S.A. *The Fluvial System*; John Wiley & Sons: New York, NY, USA, 1977; p. 338.

3.　Knighton, D. *Fluvial Forms and Processes*; Edward Arnold: London, UK, 1984; p. 218.

4.　Schumm, S.A. Geomorphic thresholds: The concept and its applications. *Trans. Inst. Br. Geogr.* **1979**, *4*, 485–515. [CrossRef]

5.　Dokuchaev, V.V. *The Ways of the River Valleys Formation at the European Russia*; Tipografiya V. Dermakova (Publ.): Sankt-Petersburg, Russia, 1878; p. 221. (In Russian)

6.　Davis, W.M. The Seine, the Meuse and the Mosell. *Geogr. Mag.* **1896**, *VII*, 189–202, 228–238.

7.　Dury, G.H. Contribution to a general theory of meandering valleys. *Am. J. Sci.* **1954**, *252*, 193–224. [CrossRef]

8.　Dury, G.H. *Principles of Underfit Streams*; US Government Printing Office: Washington, DC, USA, 1964; p. 67. Available online: https://pubs.usgs.gov/pp/0452a/report.pdf (accessed on 1 November 2020).

9.　Dury, G.H. *Theoretical Implication of Underfit Streams*; US Government Printing Office: Washington, DC, USA, 1965; p. 43. Available online: https://pubs.usgs.gov/pp/0452c/report.pdf (accessed on 1 November 2020).

10.　Volkov, I.A. Remnants of powerful flow at the valleys of southern part of the Western Siberia (Sledy moschnogo stoka v dolinakh rek yuga Zapadnoy Sibiri). *Doklady AN SSSR* **1963**, *151*, 23–25. (In Russian)

11.　Makkaveev, N.I. (Ed.) *Experimental Geomorphology (Eksperiinentalnaya Geomorfologiya)*; Moscow Univ. Press: Moscow, Russia, 1969; Volume 2, pp. 25–62. (In Russian)

12.　Goretsky, G.I. *Alluvium of the Great Anthropogene Ancient Rivers of the Russian Plain. Paleo-Rivers of the Kama Basin (Allyuviy Velikikh Antropogenovykh Prarek Russkoy Ravniny. Prareki Kamskogo Basseyna)*; Nauka (Publ.): Moscow, Russia, 1964; p. 416. (In Russian)

13.　Goretsky, G.I. *Formation of the Volga River Valley in the Early and Middle Anthropogene. Alluvium of the Ancient Volga (Formirovaniye Doliny Reki Volgi v Rannem i Srednem Antropogene. Allyuviy Pra-Volgi)*; Nauka (Publ.): Moscow, Russia, 1966; p. 412. (In Russian)

14.　Goretsky, G.I. *Alluvial Chronicle of the Great Ancient Dnieper (Allyuvial'naya Letopis' Velikogo Pra-Dnepra)*; Nauka (Publ.): Moscow, Russia, 1970; p. 492. (In Russian)

15.　Obedientova, G.V. *River Systems Formation on the Russian Plain (Formirovanie Rechnykh System Russkoy Ravniny)*; Nedra (Publ.): Moscow, Russia, 1975; p. 172. (In Russian)

16.　Grishchenko, M.N. *Pleistocene and Holocene of the Upper Don basin (Pleystotsen i Golotsen Basseyna Verkhnego Dona)*; Nauka (Publ.): Moscow, Russia, 1976; p. 228. (In Russian)

17.　Starkel, L.; Michczyńska, D.J.; Gębica, P.; Kiss, T.; Panin, A.; Perşoiu, I. Climatic fluctuations reflected in the evolution of fluvial systems of Central-Eastern Europe (60–8 ka cal BP). *Q. Int.* **2015**, *388*, 97–118. [CrossRef]

18.　Panin, A.; Adamiec, G.; Buylaert, J.-P.; Matlakhova, E.; Moska, P.; Novenko, E. Two Late Pleistocene climate-driven incision/aggradation rhythms in the middle Dnieper River basin, west-central Russian Plain. *Quat. Sci. Rev.* **2017**, *166*, 266–288. [CrossRef]

19.　Gregory, K.J. Dry valleys and the composition of the drainage net. *J. Hydrol.* **1966**, *4*, 327–340. [CrossRef]

20.　Gregory, K.J. Drainage networks and climate. In *Geomorphology and Climate*; Derbyshire, E., Ed.; John Wiley & Sons: London, UK, 1976; pp. 289–315.

21.　Eremenko, E.A.; Panin, A.V. *Mesorelief of Hollows on the East European Plain (Lozhbinnyi Mezorel'ef Vostochno-Evropeiskoi Ravniny)*; MIROS (Publ.): Moscow, Russia, 2010; p. 192. (In Russian)

22.　Panin, A.V.; Eremenko, E.A.; Kovda, I.V. The cycle of erosional dissection and filling of the erosion network in the northeast of the Stavropol Region at the end of the Pleistocene. Part I. The network of hollows. *Geomorfologiya* **2011**, *1*, 77–87. (In Russian)

23.　Panin, A.V.; Eremenko, E.A.; Kovda, I.V. The cycle of erosional dissection and filling of the erosion network in the northeast of the Stavropol Region at the end of the Pleistocene. Part II. Modern dry valleys. Erosional history of the region. *Geomorfologiya* **2011**, *2*, 102–113. (In Russian)

24. Matoshko, A.V. Balkas—A new look at a common landform of the East European Plain from a Quaternary perspective. *Earth Surf. Processes Landforms* **2012**, *37*, 1489–1500. [CrossRef]

25. Bork, H.-L. Soil erosion during the past Millennium in Central Europe and its significance within the geomorphodynamics of the Holocene. *Catena* **1989**, *15*, 121–131.

26. Bork, H.-R.; Lang, A. Quantification of past soil erosion and land use/land cover changes in Germany. In *Long Term Hillslope and Fluvial System Modelling: Concepts and Case Studies from the Rhine River Catchment*; Lang, A., Hennrich, K., Dikau, R., Eds.; Springer: Berlin/Heidelberg, Germany, 2003; pp. 231–239.

27. Larsen, A.; Heckmann, T.; Larsen, J.R.; Bork, H.-R. Gully catchments as a sediment sink, not just a source: Results from a long-term (−12,500 year) sediment budget. *Earth Surf. Processes Landforms* **2016**, *41*, 486–498. [CrossRef]

28. Hošek, J.; Prach, J.; Krizek, M.; Sida, P.; Moska, P.; Pokorny, P. Buried Late Weichselian thermokarst landscape discovered in the Czech Republic, central Europe. *Boreas* **2019**, *48*, 988–1005. [CrossRef]

29. Velichko, A.A.; Faustova, M.A.; Pisareva, V.V.; Gribchenko, Y.N.; Sudakova, N.G.; Lavrentiev, N.V. Glaciations of the East European Plain: Distribution and chronology. In *Quaternary Glaciations—Extent and Chronology. A Closer Look*; Ehlers, J., Gibbard, P.L., Hughes, P.D., Eds.; Elsevier: Amsterdam, The Netherlands, 2011; pp. 337–359.

30. Eremenko, E.A.; Panin, A.V. An origin of the net of hollows in the central and southern regions of the East European Plain. *Vestnik Mosk. Un-ta Seriya 5 Geogr.* **2011**, *3*, 59–66. (In Russian)

31. Velichko, A.A.; Pisareva, V.V.; Morozova, T.D.; Faustova, M.A.; Nechaev, V.P.; Gribchenko, Y.N. Correlation of natural events of the glacial and periglacial Pleistocene in Eastern Europe, approaches to solution. In *Quarter-2005: Materials of the IV All-Russian Meeting on the Study of the Quaternary Period (Kvarter-2005: Materialy IV Vserossiyskogo Soveshchaniya po Izucheniyu Chetvertichnogo Perioda)*; Inst. of Geology, SC URO RAS: Syktyvkar, Russia, 2005; pp. 64–66. (In Russian)

32. Velichko, A.A.; Catto, N.R.; Tesakov, A.S.; Titov, V.V.; Morozova, T.D.; Semenov, V.V.; Timireva, S.N. Structural specificity of Pleistocene loess and soil formation of the southern Russian Plain according to materials of Eastern Priazovie. *Doklady Earth Sci.* **2009**, *429*, 1364–1368. [CrossRef]

33. Grichuk, V.P. Glacial floras and their classification. In *The Last Ice Sheet in the Northwest of the European Part of the USSR (Posledniy Lednikovyi Pokrov na Severo-Zapade Evropeiskoy Chasti SSSR)*; Gerasimov, I.P., Ed.; Nauka: Moscow, Russia, 1969; pp. 57–70. (In Russian)

34. Borisova, O.K. The Holocene flora and vegetation of the northern Russian Plain (the Vychegda River basin). *Acta Palaeontol. Sin.* **2002**, *41*, 478–486.

35. Borisova, O.K.; Sidorchuk, A.Y.; Panin, A.V. Palaeohydrology of the Seim River basin, Mid-Russian Upland, based on palaeochannel morphology and palynological data. *Catena* **2006**, *66*, 53–73. [CrossRef]

36. Dodonov, A.E.; Tesakov, A.S.; Titov, V.V.; Inozemtsev, S.A.; Simakova, A.N.; Nikol'ski, P.A.; Trubikhin, V.M. New data on Pliocene-Quaternary sediments stratigraphy of the lower Don River reaches. In *Neogene and Quaternary Geological Events: Recent Status of Stratigraphical Schemes and Palaeogeographic Reconstructions (Geologicheskiye Sobytiya Neogena i Kvartera Rossii: Sovremennoye Sostoyaniye Stratigraficheskikh Skhem i Paleogeograficheskiye Rekonstruktsii)*; Gladenkov, Y.B., Ed.; GEOS (Publ.): Moscow, Russia, 2007; pp. 43–53. (In Russian)

37. Konstantinov, E.A.; Filippova, K.G. Relict erosion network in the interfluves of the eastern Azov region. *Yestestvennyye Tekhnicheskiye Nauki* **2017**, *5*, 82–88. (In Russian)

38. Konstantinov, E.A.; Velichko, A.A.; Kurbanov, R.N.; Zakharov, A.L. Middle to Late Pleistocene topography evolution of the North-Eastern Azov region. *Q. Int.* **2018**, *465*, 72–84. [CrossRef]

39. Panin, A.V.; Matlakhova, E.Y.; Belyaev, Y.R.; Buylaert, J.P.; Dubis, L.F.; Murray, A.S.; Pakhomova, O.M.; Selezneva, E.V.; Filippov, V.V. Sedimentation and formation of terraces in the river valleys of the center of the Russian Plain in the second half of the Late Pleistocene. *Bull. Kom. Izjuch. Chetv. Per.* **2011**, *71*, 47–74. (In Russian)

40. Velichko, A.A.; Morozova, T.D.; Panin, P.G. Polygenetic soil complexes as a system phenomenon of the Pleistocene macrocycles. *Izv. Akad. Nauk. Ser. Geogr.* **2007**, *2*, 44–54. (In Russian)

41. Sidorchuk, A.Y.; Borisova, O.K. Method of paleogeographical analogues in paleohydrological reconstructions. *Q. Int.* **2000**, *72*, 95–106. [CrossRef]

42. Panin, A.V.; Sidorchuk, A.Y.; Vlasov, M.V. Powerful late Valdai river flow in the Don basin. *Izy. Akad. Nauk. Ser. Geogr.* **2013**, *1*, 118–129. (In Russian)

43. Gorchakovsky, P.L.; Nikonova, N.N.; Famelis, T.V.; Sharafutdinov, M.I. Vegetation [Maps]—1:3750000. In *Atlas Sverdlovskoy Oblasti (Atlas of the Sverdlovsk Region)*; Kapustin, V.G., Kornev, I.N., Eds.; Ural Cartographic Factory: Yekaterinburg, Russia, 2003; p. 9. (In Russian)

44. Sidorchuk, A.Y.; Matveeva, T.A. Periglacial gully erosion on the East European Plain and its recent analog at the Yamal Peninsula. *GES* **2020**, *13*, 183–194. [CrossRef]

45. Sycheva, S.A. Evolution of the dry valley system in the climatic rhythm "glaciation-interglacial-glaciation". *Geomorfologiya* **1997**, *2*, 100–111. (In Russian)

46. Sycheva, S.A. Evolution of the Moscow-Valdai paleo-incisions on the interfluves of the Middle Russian Upland. *Geomorfologiya* **2003**, *3*, 76–91. (In Russian)

47. Sycheva, S.A. Evolution of buried dry valley landscapes of the forest-steppe of the Russian Plain. *Izv. Akad. Nauk. Ser. Geogr.* **2003**, *1*, 1–11. (In Russian)

48. Belyaev, Y.R.; Grigorieva, T.M.; Sycheva, S.A.; Sheremetskaya, E.D. Development of the dry valley upper reaches in the central Middle Russian Upland at the end of the Middle-Late Pleistocene. *Geomorfologiya* **2008**, *1*, 43–55. (In Russian)

49. Sycheva, S.; Frechen, M.; Terhorst, B.; Sedov, S.; Khokhlova, O. Pedostratigraphy and chronology of the Late Pleistocene for the extra glacial area in the Central Russian Upland (reference section Aleksandrov quarry). *Catena* **2020**, *194*, 104689. [CrossRef]

50. Panin, A.V. The upper reaches of the channel-dry valley systems of the East European Plain in glacial-interglacial climatic rhythms. In *Eroziya Pochv i Ruslovyye Protsessy (Soil Erosion and Channel Processes)*; Chalov, R.S., Ed.; Moscow Univ. Press: Moscow, Russia, 2012; Volume 18, pp. 92–114. (In Russian)

51. Panin, A.V.; Malaeva, E.M.; Golosov, V.N.; Ivanova, N.N.; Markelov, M.V. Geological and geomorphological structure and Holocene history of the development of Berestovaya Balka (Rostov Region). *Geomorfologiya* **1998**, *4*, 70–85. (In Russian)

52. Sidorchuk, A.Y.; Borisova, O.K.; Panin, A.V.; Chernov, A.V. Evolution of erosion-channel systems on the East European Plain in the last 150 thousand years. In *Proc. Conf. "Readings in Honour of N.I. Makkaveev—2013"*; Moscow State Univ., Geogr. Faculty: Moscow, Russia, 2014; pp. 117–138. Available online: https://istina.msu.ru/publications/article/7763760/ (accessed on 1 November 2020). (In Russian)

53. Panin, A.V.; Nekrasov, D.Y. The Pokrovskiy Log balka history at the Kostenki 14 site. In *Paleosols, Pedosediments and Landscape Morphology as Archives of Environmental Evolution. Guidebook for field excursions: XIIth International Symposium and Field Workshop on Paleopedology (ISFWP)*; Kovda, I.V., Ed.; Inst. of Geography RAS: Moscow, Russia, 2013; pp. 74–79.

54. Matlakhova, E.Y.; Panin, A.V.; Belyaev, Y.R.; Borisova, O.K. Development of the Upper Don valley at the end of the Late Pleistocene. *Vestnik Mosk. Un-ta Seriya 5 Geogr.* **2019**, *3*, 83–92. (In Russian)

55. Sidorchuk, A.; Borisova, O.; Panin, A. Fluvial response to the late Valdai/Holocene environmental change on the East European Plain. *Glob. Planet. Chang.* **2001**, *28*, 303–318. [CrossRef]

56. Panin, A.V.; Sidorchuk, A.Y. Macro-bands ("large meanders"): Problems of origin and interpretation. *Vestnik Mosk. Un-ta Seriya 5 Geogr.* **2006**, *6*, 14–22. (In Russian)

57. Dreibrodt, S.; Hofmann, R.; Sipos, G.; Schwark, L.; Videiko, M.; Shatilo, L.; Martini, S.; Saggau, P.; Bork, H.-R.; Kirleis, W.; et al. Holocene soil erosion in Eastern Europe-land use and/or climate controlled? The example of a catchment at the Giant Chalcolithic settlement at Maidanetske, central Ukraine. *Geomorphology* **2020**, *367*, 107302. [CrossRef]

58. Stange, K.M.; Midtkandal, I.; Nystuen, J.P.; Murray, A.; Sohbati, R.; Thompson, W.; Spiegel, C.; Kuss, H.-J. Erosive response of non-glaciated Pyrenean headwater catchments to the last major climate transition and establishing interglacial conditions. *Quaternary* **2019**, *2*, 17. [CrossRef]

59. Vandenberghe, J.; Sidorchuk, A. Large palaeomeanders in Europe: Distribution, formation process, age, environments and significance. In *Palaeohydrology. Geography of the Physical Environment*; Herget, J., Fontana, A., Eds.; Springer Nature: Cham, Switzerland, 2019; Chapter 9; pp. 169–186.

60. Matoshko, A.V.; Gozhik, P.F.; Danukalova, G. Key Late Cenozoic fluvial archives of Eastern Europe: The Dniester, Dnieper, Don and Volga. *Proc. Geologists' Assoc.* **2004**, *115*, 141–173. [CrossRef]

61. Vandenberghe, J. The fluvial cycle at cold-warm-cold transitions in lowland regions: A refinement of theory. *Geomorphology* **2008**, *98*, 275–284. [CrossRef]

62. Bridgland, D. The record from British Quaternary river systems within the context of global fluvial archives. *J. Quat. Sci.* **2010**, *25*, 433–446. [CrossRef]

63. Lisiecki, L.E.; Raymo, M.E. A Pliocene-Pleistocene stack of 57 globally distributed benthic d18O records. *Paleoceanography* **2005**, *20*, PA1003. [CrossRef]

64. Waelbroeck, C.; Labeyrie, L.; Michel, E.; Duplessy, J.C.; McManus, J.F.; Lambeck, K.; Balbon, E.; Labracherie, M. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. *Q. Sci. Rev.* **2002**, *21*, 295–305. [CrossRef]

65. Sidorchuk, A.Y.; Panin, A.V.; Borisova, O.K. River runoff in the East European Plain over the past 20 thousand years and the problem of changes in the levels of the southern seas. In *Voprosy Geografii. Vol. 145. Gidrologicheskiye Izmeneniya (Problems of Geography. Vol. 145. Hydrological Changes)*; Kotlyakov, V.M., Koronkevich, N.I., Barabanova, E.A., Eds.; "Kodeks" Publ. House: Moscow, Russia, 2018; pp. 144–168. (In Russian)

66. Velichko, A.A.; Zelikson, E.M.; Borisova, O.K.; Gribchenko, Y.N.; Morozova, T.D.; Nechayev, V.P. Quantitative reconstructions of the climate of the East European Plain for the last 450 thousand years. *Izv. Akad. Nauk. Ser. Geogr.* **2004**, *1*, 7–25. (In Russian)

67. Li, C.X.; Ivanov, V.; Fan, D.D.; Korotaev, V.; Jang, S.J.; Chalov, R.S.; Liu, S.G. Development of the Volga delta in response to Caspian Sea-level fluctuation during last 100 years. *J. Coastal Res.* **2004**, *20*, 401–414. [CrossRef]

68. Popov, G.I. *Pleistocene of the Black Sea—Caspian Sea Straights (Pleistotsen Chernomorsko-Caspiiskikh Prolivov)*; Nauka: Moscow, Russia, 1983; p. 216. (In Russian)

69. Ivlieva, O.V.; Berdnikov, S.V. Recent destruction rates of the Azov beaches in Russia. *Geomorfologiya* **2005**, *4*, 74–83. (In Russian) [CrossRef]

70. Høyer, A.-S.; Jørgensen, F.; Sandersen, P.B.E.; Viezzoli, A.; Møller, I. 3D geological modelling of a complex buried-valley network delineated from borehole and AEM data. *J. Appl. Geophys.* **2015**, *122*, 94–102. [CrossRef]

71. NorthGRIP Members. High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature* **2004**, *431*, 147–151. [CrossRef]

72. Sidorchuk, A.; Panin, A.; Borisova, O. Surface runoff to the Black Sea from the East European Plain during Last Glacial Maximum–Late Glacial time. In *Geology and Geoarchaeology of the Black Sea Region: Beyond the Flood Hypothesis*; Buynevich, I., Yanko-Hombach, V., Gilbert, A.S., Martin, R.E., Eds.; Geological Society of America: Boulder, CL, USA, 2011; pp. 1–25.

73. Sidorchuk, A.Y.; Panin, A.V.; Borisova, O.K. Morphology of river channels and surface runoff in the Volga River basin (East European Plain) during the Late Glacial period. *Geomorphology* **2009**, *113*, 137–157. [CrossRef]

74. Sidorchuk, A.; Panin, A.; Borisova, O.; Kovalyukh, N. Lateglacial and Holocene palaeohydrology of the lower Vychegda river, western Russia. In *River Basin Sediment Systems: Archives of Environmental Change*; Maddy, D., Macklin, M.G., Woodward, J.C., Eds.; A.A. Balkema Publishers: Boca Raton, FL, USA, 2001; pp. 265–295.

75. Sidorchuk, A.Y.; Panin, A.V.; Borisova, O.K. Climate-induced changes in surface runoff on the North-Eurasian plains during the Late Glacial and Holocene. *Water Resour.* **2008**, *35*, 386–396. [CrossRef]

76. Sidorchuk, A.Y. Organic carbon in redeposited soil matter and modern carbon dioxide emissions as a result of erosion-accumulative processes in the Don River basin. In *Proc. Conf. "Readings in Honour of N.I. Makkaveev—2018"*; Moscow State Univ., Geogr. Faculty: Moscow, Russia, 2018; pp. 105–115. Available online: https://istina.msu.ru/publications/article/153954212/ (accessed on 1 November 2020). (In Russian)

77. Bahr, A.; Arz, H.W.; Lamy, F.; Wefer, G. Late Glacial to Holocene paleoenvironmental evolution of the Black Sea, reconstructed with stable oxygen isotope records obtained on ostracod shells. *Earth Planet. Sci. Lett.* **2006**, *241*, 863–875. [CrossRef]

78. Sidorchuk, A. The fluvial system on the East European Plain: Sediment source and sink. *GES* **2018**, *11*, 5–20. [CrossRef]