ИНСТИТУТ ГЕОГРАФИИ
Российской академии наук
основан в 1918 году

Deciphering the pedogenic and sedimentary archives and long-term landform dynamics to reconstruct complex landscape evolution within a lowland gully catchment over the Holocene

V.R. Belyaev[1,2], I.G. Shorkunov[1], E.V. Garankina[1,2], E.A. Konstantinov[1], A.V. Rusakov[3,4],

Yu.V. Shishkina[1,2], P.V. Andreev[1]and T.A. Verlova[3]

[1] Institute of Geography, Russian Academy of Sciences, 29, Staromonetny lane, Moscow, 119017, Russia

[2] Lomonosov Moscow State University, MSU main building, 1-1, Leninskie Gory, Moscow, 119991, Russia

[3] Saint Petersburg State University, 7-9, Universitetskaya nab., Saint Petersburg, 199034, Russia

[4] Herzen State Pedagogical University of Russia, 48, Moika nab., Saint Petersburg, 191186, Russia

vladimir.r.belyaev@gmail.com

Carried out under support of the Russian Science Foundation project 19-77-10061

Session SSS8.8 | D2154 | EGU2020-13190

Introduction

It is widely accepted that interfluvial landscapes of vast European plains have been subject to alternating periods of relative stability and significant up to catastrophic shifts in climate, soil and geomorphological evolution in the Holocene. Over the entire Northern Europe forested territories, there are numerous examples of Holocene landscape disturbance even before the onset of widespread agriculture.

For the landscape and climatic conditions of the Eastern European Plain fluvial processes are considered to be the leading geomorphic force during the Holocene. Various fluvial system components including gully erosion, river channel and floodplain processes are characterized by various degrees of resilience and relaxation times in response to external impacts of different duration, magnitude and frequency. Hillslope processes, on the other hand, including slope wash and mass wasting, reflect another significant agent of landscape instability. The Late Glacial interfluvial and gentle slope landscapes outside the glaciation boundary were dominated by various types of cryogenic processes, which left profound heritage in both soil-sedimentary and surface topography structures and still exert significant influence on soil formation and geomorphic processes.

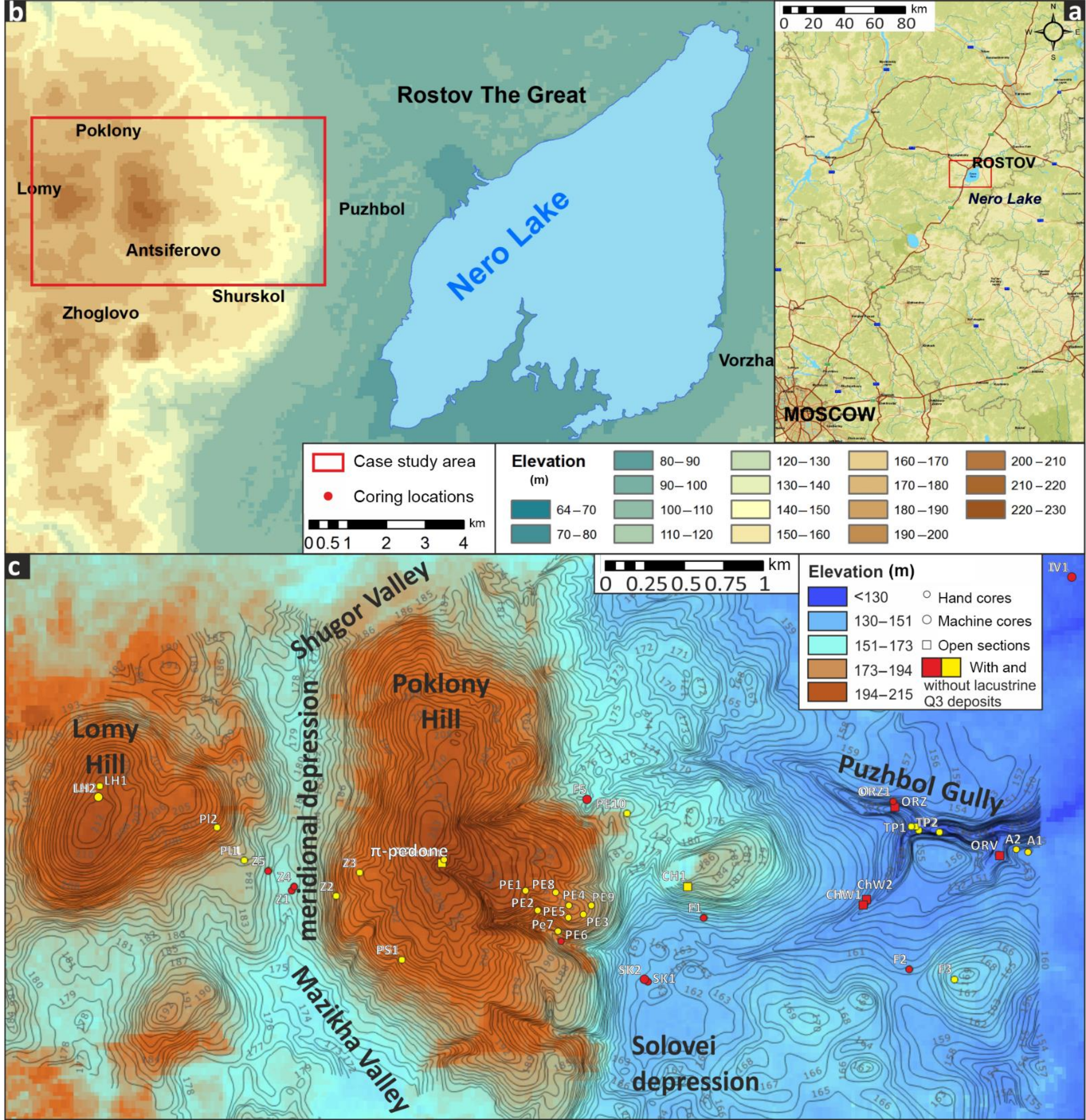
This paper presents the new results of comprehensive investigations of the Holocene dynamics of fluvial and related processes including soil formation during landscape stabilization phases for one of the gully catchments draining the Borisoglebsk Upland northeastern slope towards the Nero Lake local baselevel.

General position of the case study area:

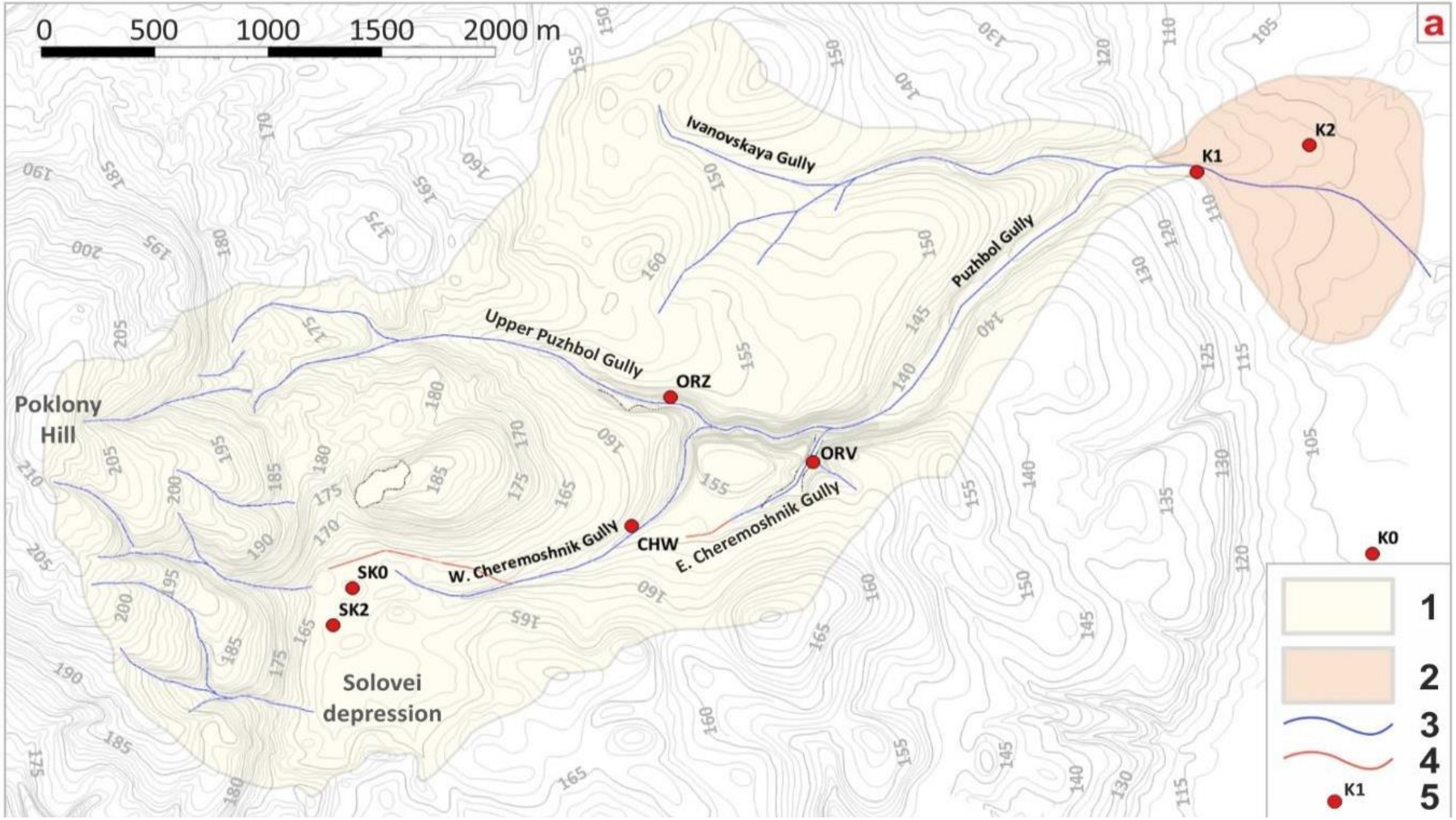
Northeastern Borisoglebsk Upland at elevations 140-214 m asl is dominated by hilly glacial landforms significantly reworked by fluvial incisions and even more extensively by local lacustrine accumulations in numerous linear and closed depressions. Generally classified as southern taiga region, modern landscapes are extensively influenced by human activity and, thus, have patched structure with a predominance of agricultural fields, secondary small-leaved forests and limited areas of coniferous forests and bogs.

Active gullies and small valleys incise interfluves down to 15-25 m and commonly have V-shaped or trapezoidal cross-sections. The long profiles of such gullies with steps and convexities represent a certain potential for further incisions. Larger gully systems and small valleys usually have a series of smaller gully branches dissecting their steep slopes.

Nero Lake represents the main local baselevel at 93.2 m asl. However, wide (1.0-2.5 km) lake terrace at 105-107 m asl presently disconnects most gullies from the lake. Instead, they form large fans overlapped on the terrace. It was accumulated during the Late Valdai, and the terrace had isolated due to the Nero Lake level fall during the Late Valdai - Holocene transition.



The case study area – Puzbol Gully catchment



Detailed topography of the Puzbol Gully catchment and surrounding areas based on the 1 : 10000 land planning topographic map (contour interval 1 m). 1 – Puzhbol Gully catchment, 2 – Puzhbol Gully fan, 3 – thalwegs, 4 – artificial drainage ditches, 5 – positions of key cores/sections.

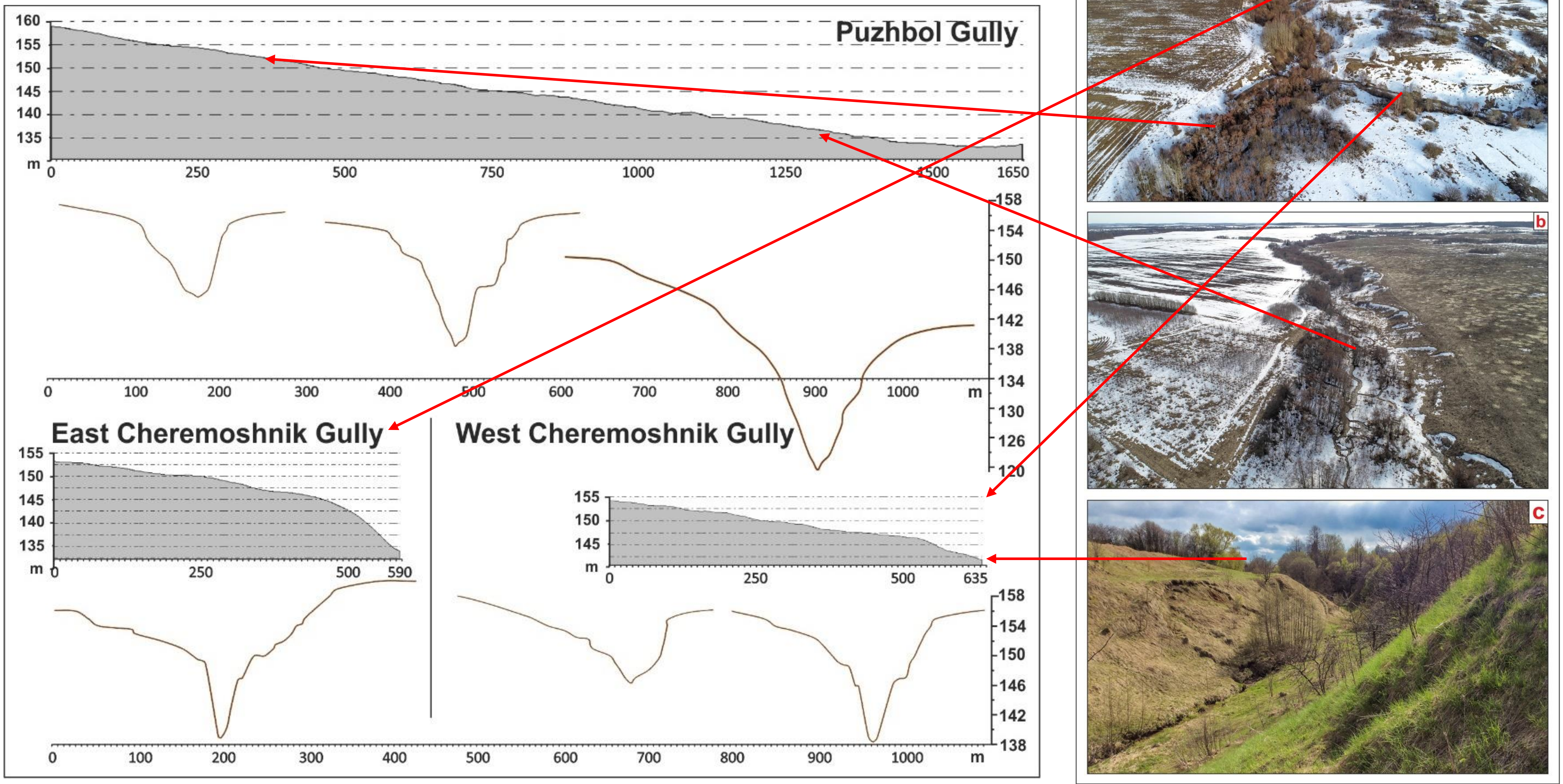
The Puzhbol Gully catchment:

Area 7.95 km^2

The eastern slope of the Poklony Hill and lower interfluvial steps down to the slope towards the Nero Lake terrace (105-107 m asl), which is partly covered by a large gully fan. Complex topography with the main gully, one large left (Ivanovskaya) and two smaller right (West and East Cheremoshnik) tributaries.

The main gully is about 3 km long, has a curved planform with the general eastern direction and uneven stepped long profile with variable gradient 1-3%. Total elevation range between gully head and fan apex is about 50 m. Maximum incision depth reaches 20-25 m, width changes from 20-30 to 250-270 m, cross-section profiles – from V-shaped in upper to U-shape in middle and trapezoidal in lower part.

Typical long and cross-section profiles and views of the three main gullies within the studied catchment



Research Methods and Techniques

Investigations of composition of surface drifts, slope, alluvial and lacustrine deposits and underlying glacial, glaciofluvial and limnoglacial tills within the Puzhbol gully system catchment have been carried out by means of detailed field description, photo-fixation and sampling of hand (diameter 3 cm) and machine (diameter 8-10 cm) corings, soil sections, natural (active gully banks) and artificial (sand and gravel quarry) exposures. Textural and structural description of cores and pits on macro- and meso scales was supplemented by sampling with 5 to 10 cm interval, taking into account sedimentary and pedogenic features variability.

Cores/sections and the UAV survey ground control and reference points positions were obtained by post-processing differential GNSS survey with Leica GX 1200 base-rover complex achieving horizontal error < ±2 cm and vertical < ±10 cm.

Open-source remote sensing data including satellite imagery DigitalGlobe/GeoEye (Google Earth service), IRS and LANDSAT (Yandex Maps service) and global satellite radar DEMs (SRTM and ALOS 3D), small-scale land planning topographic maps and aerial photography obtained by unmanned aerial vehicle (UAV) DJI Phantom IIIpro and IVpro were used for the detailed geomorphological evaluation of the area and morphometric analysis.

Grain size analysis involved standard sample preparation, dry sieving separation of the coarser fractions (>100 μm) with sieve shaker Fritsch Analysette 3 PRO and laser diffractometry of the finer component (<100 μm) with Fritsch Analysette Nanotek 22.

Organic and chemical carbon contents were estimated by successive weight loss on ignition at 500°C and 900°C.

Radiocarbon dating of organic-rich layers was carried out using AMS technique at the Laboratory of Radiocarbon Dating and Electronic Microscopy, Institute of Geography, Russian Academy of Sciences, and using LSC technique at the Kyiv Radiocarbon Laboratory, Institute of Environmental Geochemistry, National Academy of Science of Ukraine. The results are summarized in table 1.

Table 1. List of the uncalibrated ^{14}C dates obtained within the study area.

No	Section	Lab code	H_{abs}, m	Depth, cm	Location	Description	Dated Material	^{14}C, yrs BP
1	K2	ЛУ-9325	106,5	125-135	Puzhbol Gully fan	gyttja	TOC[1]	**610±70**
2	K0	SOAN-3002	104,7	<100	colluvial fan at the Nero Lake terrace	peat overlayed by thin agrogenic colluvial deposits	HA[1]	**830±20**
3	ORV	IGAN-2654	146.8	140-150	East Cheremoshnik Gully	Buried humus horrizon	HA	**2630±90**
4	SK2	Ki-19676	161.8	096-102	Solovei depression	gyttja	TOC	**5190±60**
5	ChW1	Ki-19670	153.8	100-105	West Cheremoshnik Gully	charcoal-rich colluvial/alluvial loam	TOC	**5450±80**
6	SK0	IGAN-2535	164	65	Solovei depression	gyttja	HA	**5600±140**
7	ORZ	LU-7819	151.6	170-190	Puzhbol Gully, upper reaches	charcoal-rich colluvial loam	TOC	**5670±130**
8	K1	LU-9324	111,5	143-149	Puzhbol Gully fan	gyttja	TOC	**5720±190**
9	ORV	Ki-16679	146.8	180-210	East Cheremoshnik Gully	coarse-debris lens with plant rests	Plant rs.	**9870±120**
10	K1	IGANAMS-6668	111,5	575-590	Puzhbol Gully fan	lacustrine sandy silts with disperse plant rests	Plant rs.	**12310±30**
11	ORV	IGAN-4048	146.8	220-230	Cheremoshnik East	thin organic-rich interlayer in coarse debris alluvial sediments	HA	**12570±440**

Types of pedo-sedimentary records observed:

There are four main types of paleoarchives distinguished on the basis of detailed soil and lithostratigraphic survey of the catchment, which we can use to reconstruct the Puzhbol gully system dynamics. Their determination was based on geological composition, geomorphic position and kind of record, as described below in more detail.

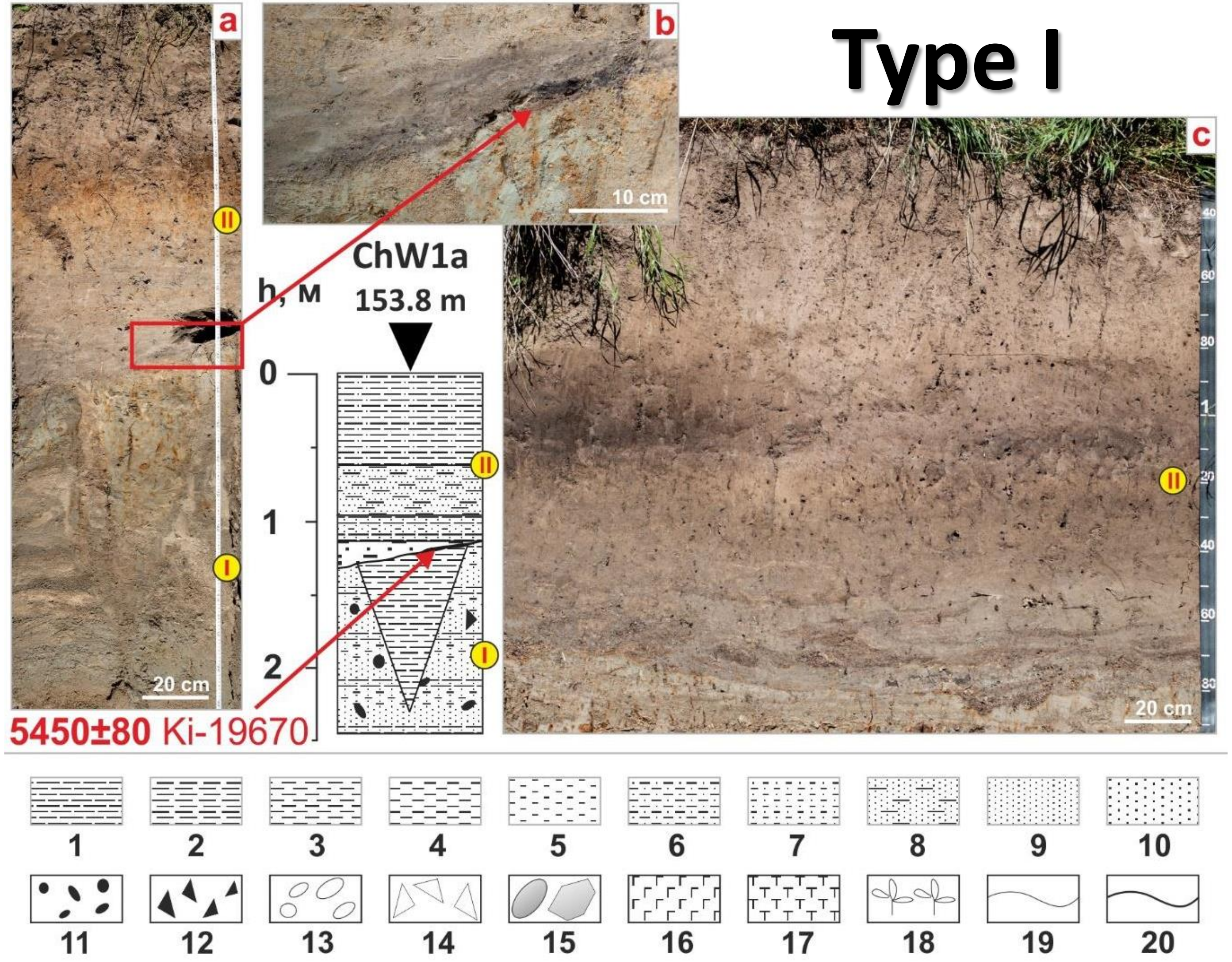
I) **The first type** **includes cyclic pedolithosediments, both natural pre-agrogenic and agriculture-initiated accelerated soil erosion colluvium, gully alluvium and complex of pre-agrogenic slope deposits of variable origin, exposed in active gully banks.**

II) **The second type** **main distinction is the prevalence of solid-phase deposition sometimes accompanied with short-term embryonal soil formation over denudation and spatially is bound to closed depressions within the interfluvial areas.**

III) **The third type** **is represented by polycyclic sod-podzolic (Retisols) texture-differentiated soils present in a sequence of the Holocene slope deposits in area not affected by gully erosion. There are several overlapped or partially welded buried soil profiles and horizons, which can be interpreted as different surfaces with relatively long-term exposure.**

IV) **The fourth type** **is associated with large fan of the Puzhbol gully system superimposed onto one of the Nero Lake terraces (105-107 m) dated up to 610±70 yrs BP and composed of interbedded gully alluvium and lake sediments overlain by the agrogenic period colluvium.**

Type I



Lithology (here and on next figures): 1 – clay, 2 – silt, 3 – heavy loam, 4 – loam, 5 – light loam, 6 – sandy loam, 7 – loamy sand, 8 – silty sand, 9 – fine sand, 10 – medium to coarse sand, 11 – rounded gravel, 12 – angular gravel, 13 – rounded pebble, 14 - angular pebble, 15 – boulders, 16 – gyttja, 17 – peat, 18 – plant rests, 19 – stratigraphic boundaries, 20 – erosive contacts.

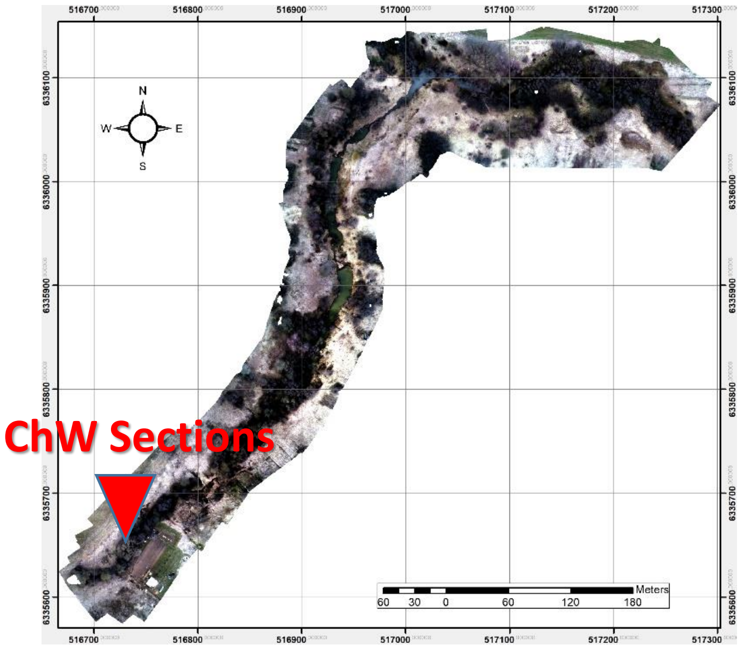
Cryogenic, erosional and pedo-sedimentary features observed on the left bank of the West Cheremoshnik Gully.

<u>Section CHW1:</u>

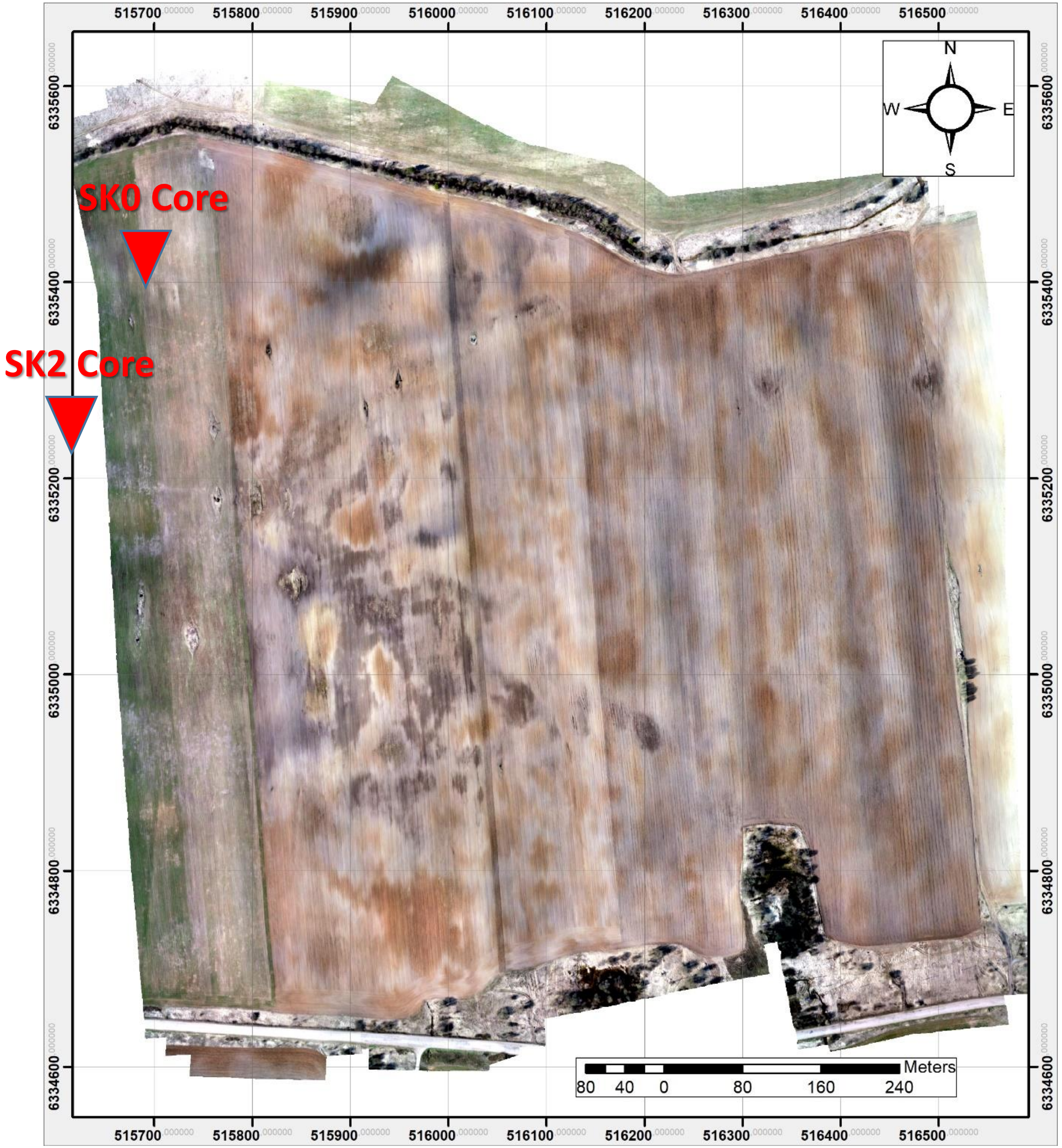
a) general view of the loam-filled wedge in Late Valdai clayey sands truncated by erosional boundary;

b) sandy lens with localized accumulation of organic-rich material at the right margin;

c) Section CHW2 (about 30 m downstream) with similar general stratigraphy but evidence of paleosol formation at depths of 110-130 cm.



Relic cryogenic features within the study area mapped by the UAV surveys



Type I

Upper part of the ORZ section on the left bank of the Puzhbol Gully:

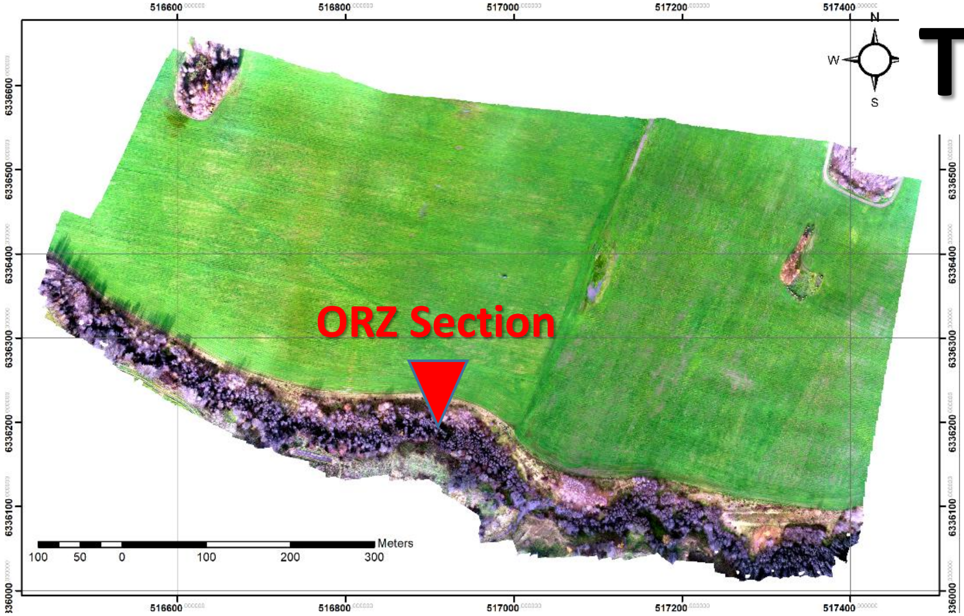
a) general view of the Holocene silty loam colluvium;

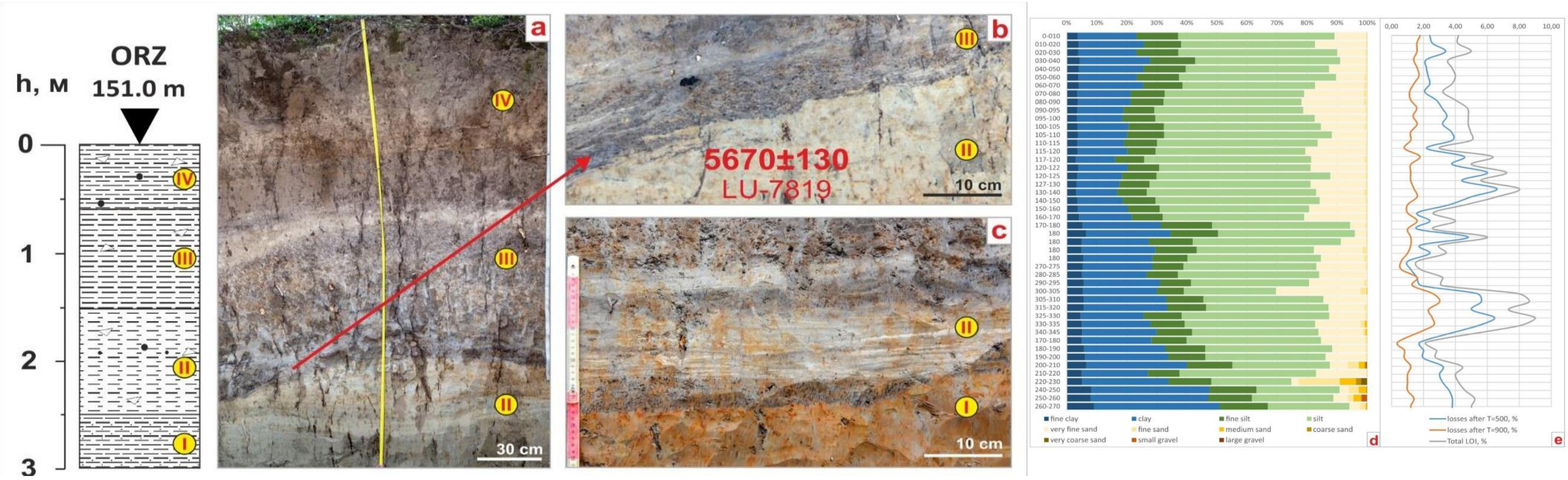
b) ^{14}C dated basal layer of the Holocene colluvium (unit III);

c) contrastingly stratified silt loam (unit II): natural soil erosion cyclic colluvium underlain by contrast mottled cover beds (unit I);

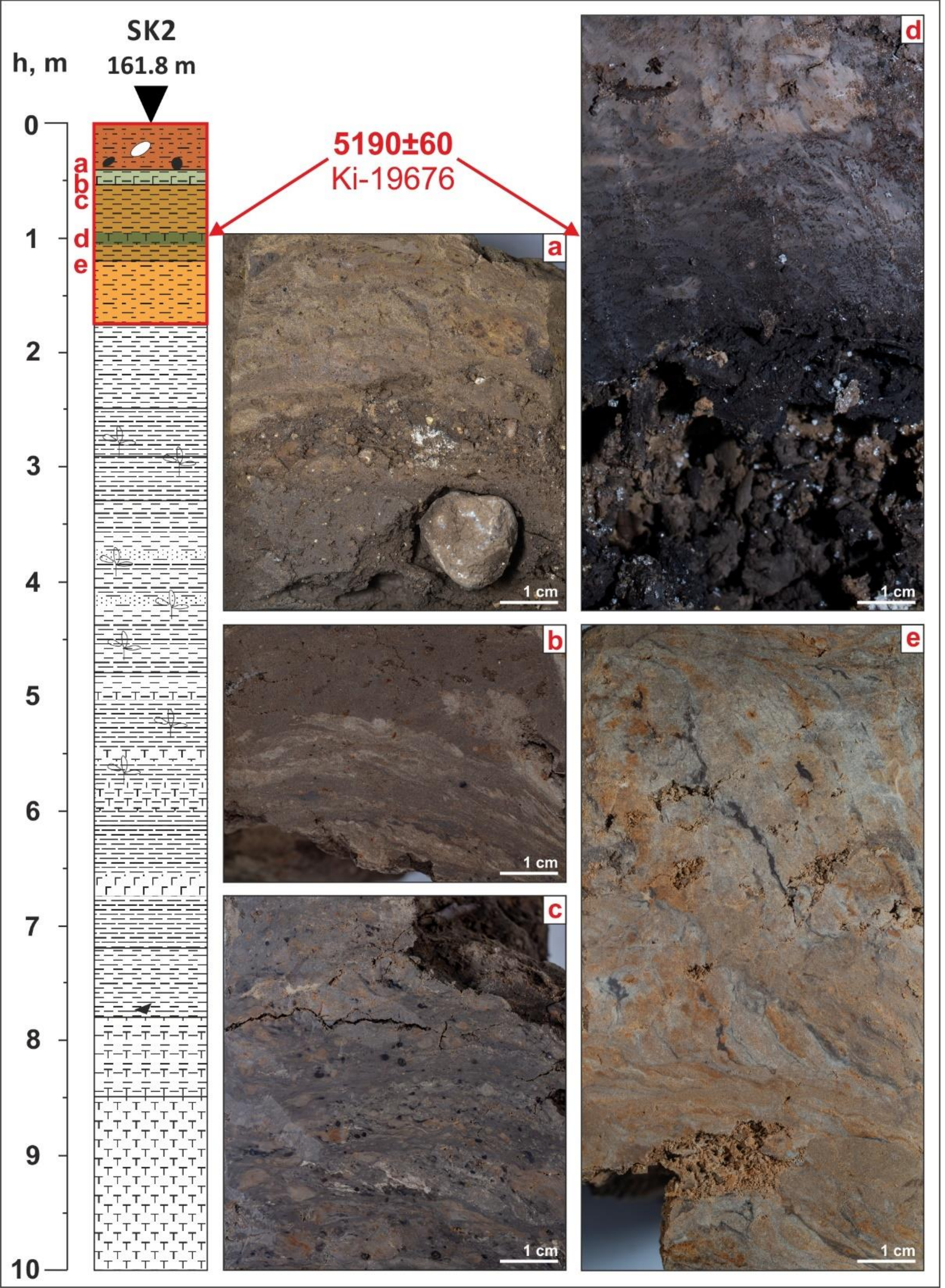
d) results of grain size analysis;

e) loss on ignition.

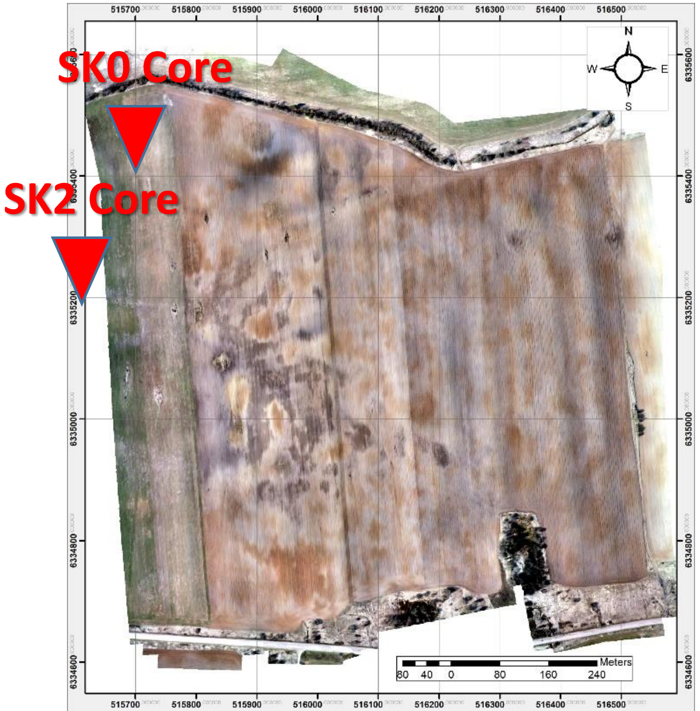




Type II

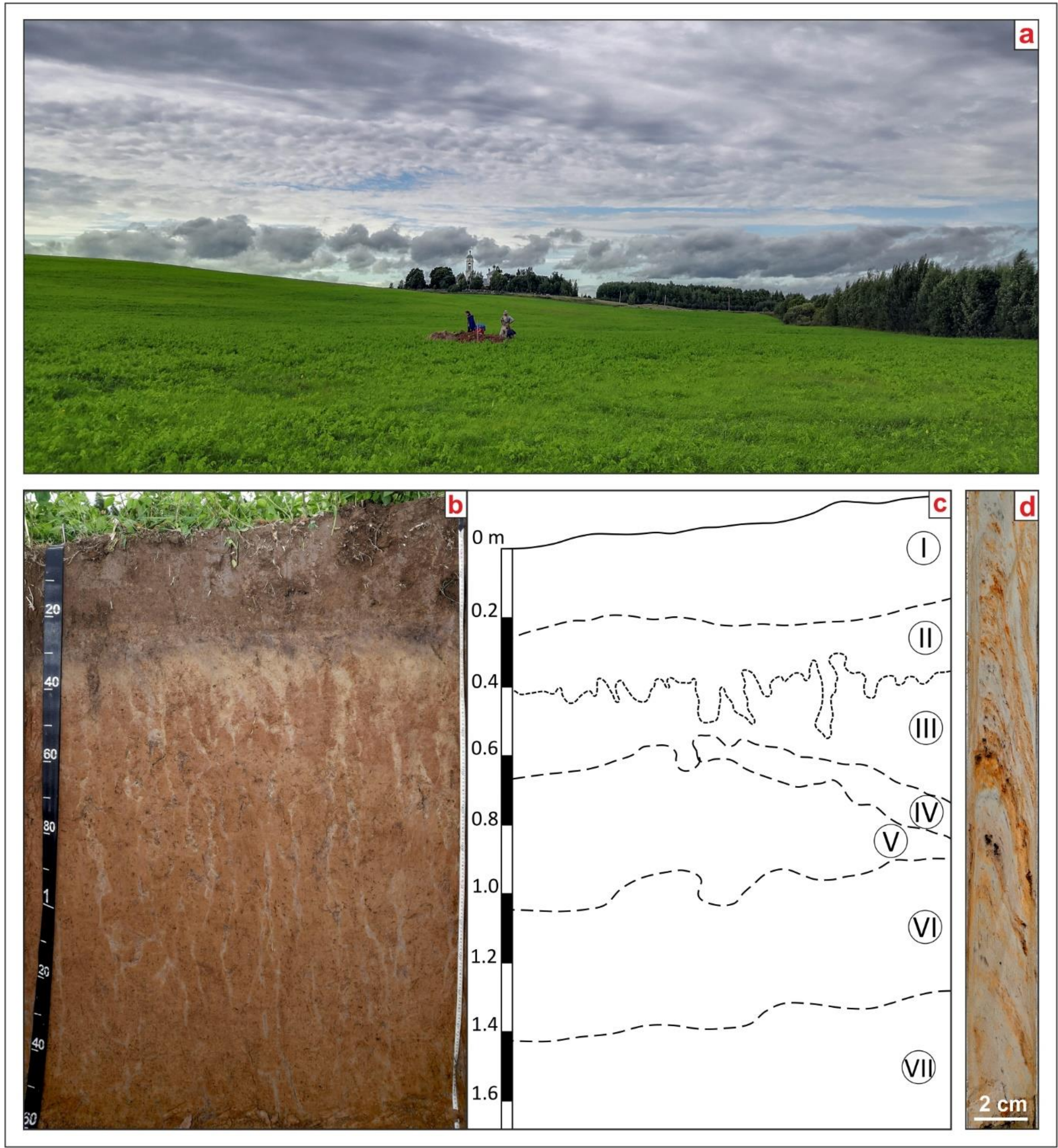


Selected pedo-sedimentary features of the core SK2:
a) coarse clasts impregnated in sandy loam matrix (33-40 cm);
b) organic-rich fine-laminated layer (50-55 cm); c) mottled laminated layer (60-70 cm);
d) peat layer (94-100 cm);
e) bright mottled unit with a set of non-conform
contacts between wavy and inclined laminated beds (106-113 cm).



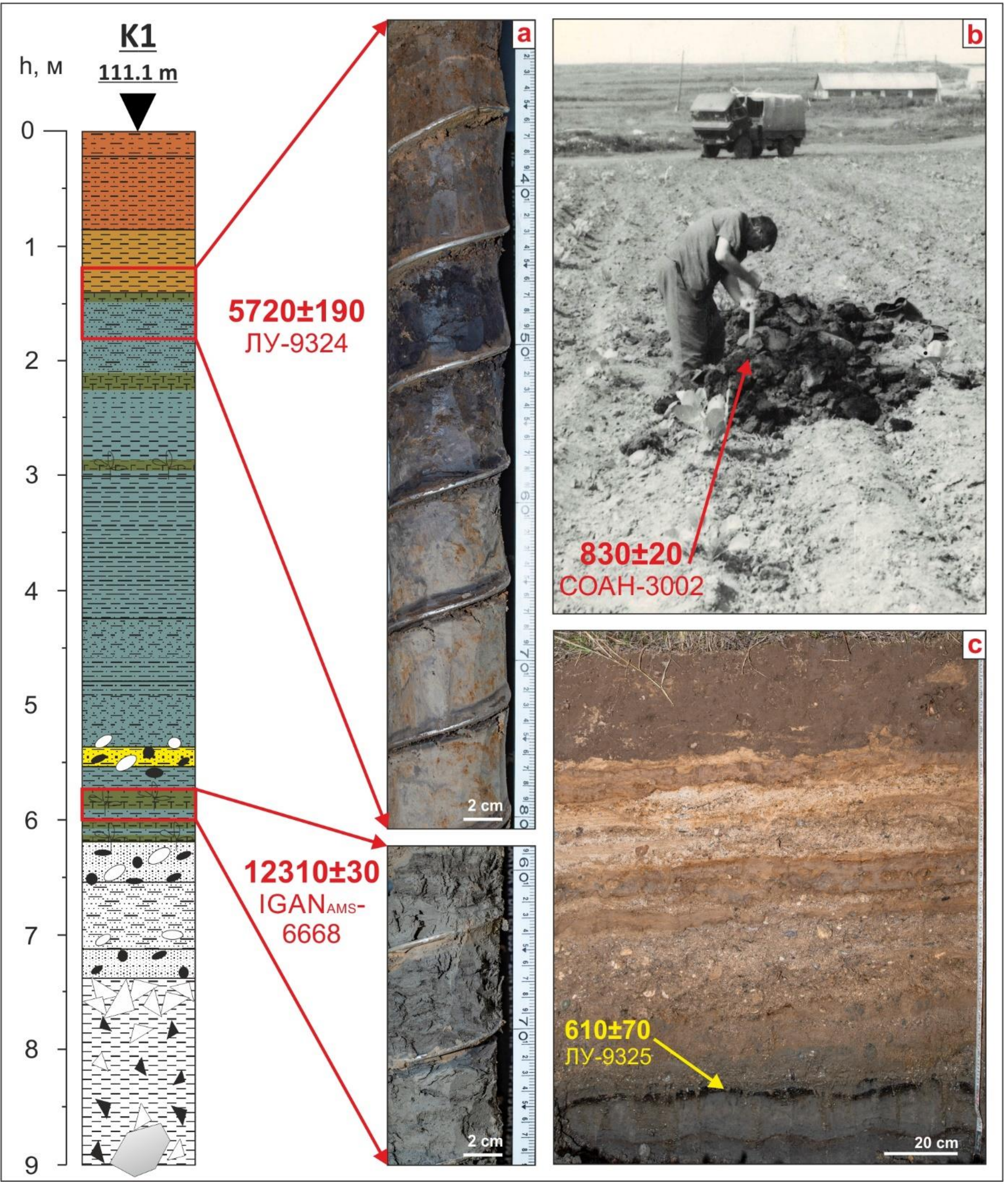
Type III

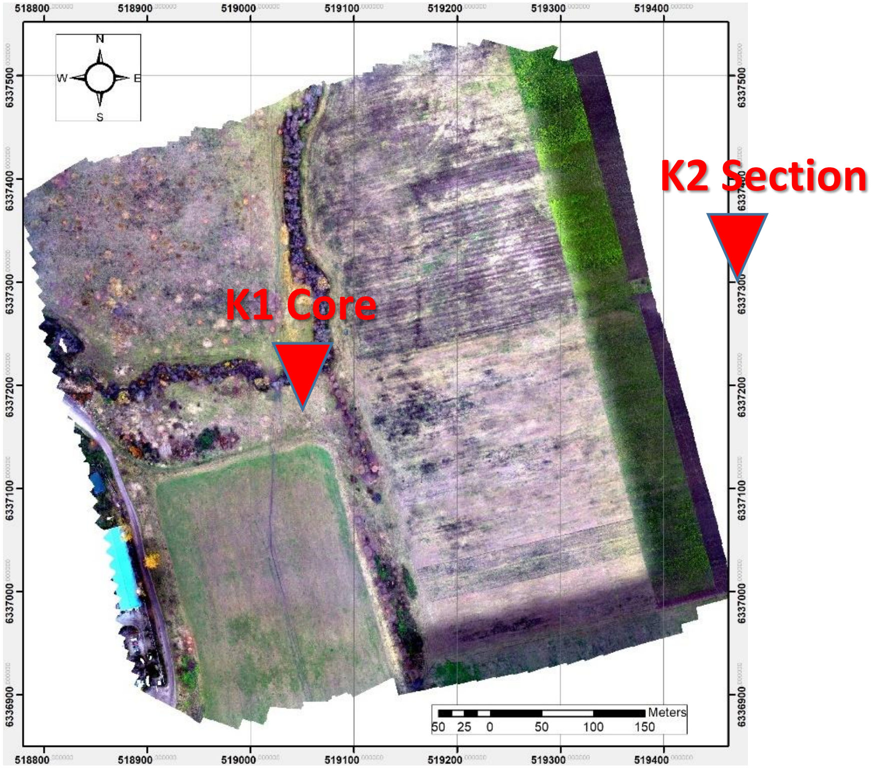
Soils of the upper reaches of the Puzhbol catchment:
a) general view of the Poklony hill north-eastern footslope, PE12 pit in the center;
b) complex profile of polycyclic sod-podzolic soil (Retisol);
c) lithological complexity of the soil body;
d) hand core of contrastingly laminated Late Valdai lacustrine deposits in the base of the section.



Type IV

The Puzhbol Gully system fan and underlying deposits:
a) core K1 and magnified photos of its key dated parts;
b) general view of section K0 by A.V. Rusakov
(1980s) and associated age of the agrogenic colluvium base;
c) section K2 and location of material sampled in order to date the base of the gully fan.





General Results

- ✓ Detailed investigation of slope deposits within the Puzhbol Gully catchment discovered high textural variability of colluvial facies including both those produced by solifluction and slope wash under pre-Holocene periglacial conditions and the warmer Holocene colluvium formed solely by hillslope water erosion. The latter bears clear evidence of several pyrogenic events (layers rich in buried charcoal). Previously published data (Rusakov et al., 2015, Shishkina et al., 2019) allows suggesting that the beginning of the Late Valdai incision happened around 12570±440 14C yrs BP (IGAN-4048) followed by successive alluvial infill till the early Holocene (9870±120 14C yrs BP, Ki-16679). It is likely that general fluvial incision occurred in the entire Nero Lake basin following its level fall from 107-110 m to <95 m asl (Wohlfarth et al., 2006).
- ✓ Absence of soil remnants formed during the first half of the Holocene on eroded surface of the Late Valdai deposits and lack of even associated sedimentary sequences in several sections (ChW, ORV, ORZ) can be explained by generally negative sediment budget of the catchment. Continuous erosion was not likely under completely forested landscape conditions. However, rare climatic extremes, such as catastrophic millenia-scale rainfall reported for Western Europe in July 1342, or fire-induced erosion events (Bertran, 2004; Dotterweich, 2008) could probably be the case.

General Results

- ✓ Although with a limited number of dates available so far, there appears to be a period of time between approximately 5000 and 6000 ^{14}C yrs BP where dates from all the studied objects are present. For upper (Solovei depression) and lower (Puzhbol Gully fan) parts of the catchment such dates signify certain stabilization periods, while for the middle part (sections ORZ and CHW1-2 in eroded gully banks) - periods of change of local evolution trend from incision to infill. Does it represent any specific relationship, or just a pure coincidence, remains a question for further research.

- ✓ Upper part of the Puzhbol Gully system fan sediment bears clear evidence of synchronous formation of agrogenic colluvium (started not earlier than XIIth Century AD) and gully alluvium more than 1 m thick (basal layer dated to 610±70 ^{14}C yrs BP) covering the lake terrace deposits. It is in accordance with the reported human impact on erosion processes in Central European Russia that became significant since the 11th century AD, and, more confidently, since the 14th–16th centuries (Panin et al., 2009).

Research Perspectives

Further research will involve calculation of the Puzbol Gully catchment soil redistribution rates and sediment delivery ratios for several different pre-historic landscape and historic land use structure scenarios using the two independent models:

1) The empirical-mathematical model (EMM) utilizing a combination of the RUSLE-based approach for estimating rainfall-induced sheet erosion (Renard et al., 1994) and the model developed by the Russian State Hydrological Institute for estimating sheet erosion from snowmelt runoff (Bobrovitskaya, 2002). It was specially designed for application under Russian conditions and is provided with a large spatially distributed dataset of coefficients (Larionov et al., 1998; Belyaev et al., 2005).
2) The widely used and extensively tested at different scales from elementary slope units to the European countries spatially distributed WaTEM/SEDEM model developed at the KU Leuven (Belgium) Division of the Geography and Tourism, Geomorphic processes, soil degradation and soil conservation research group.

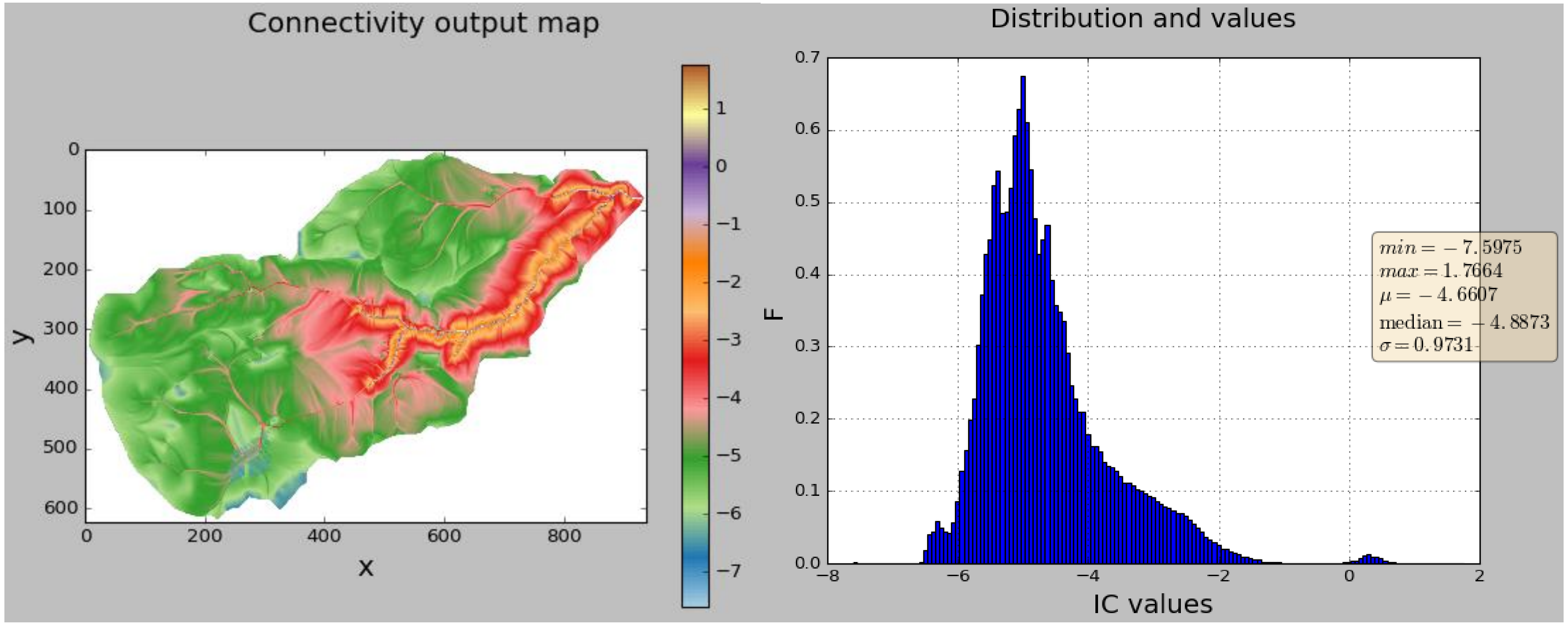
https://ees.kuleuven.be/geography/modelling/watemsedem/index.html

Borrelli, P., Van Oost, K., Meusburger, K., Alewell, C., Lugato, E., Panagos, P. 2018. A step towards a holistic assessment of soil degradation in Europe: Coupling on-site erosion with sediment transfer and carbon fluxes. Environmental Research, 161: 291-298.

Research Perspectives 2

For reliable transition from calculated soil redistribution rates within the landscape units determined to sediment delivery ratios, two approaches will be involved:

1) Comparison of the calculated ranges of eroded volumes for different scenarios with correlated sediment volumes directly detected by our geological investigations.
2) Evaluation of probability range of sediment transfer between the landscape units determined for different scenarios based on geomorphic and sediment connectivity approach as proposed by Borselli et al. (2008) and Cavalli et al. (2013), with some modifications of the impedance of runoff and sediment fluxes weighting factor W (will be estimated as RUSLE C coefficient modified for the Russian version of the model).

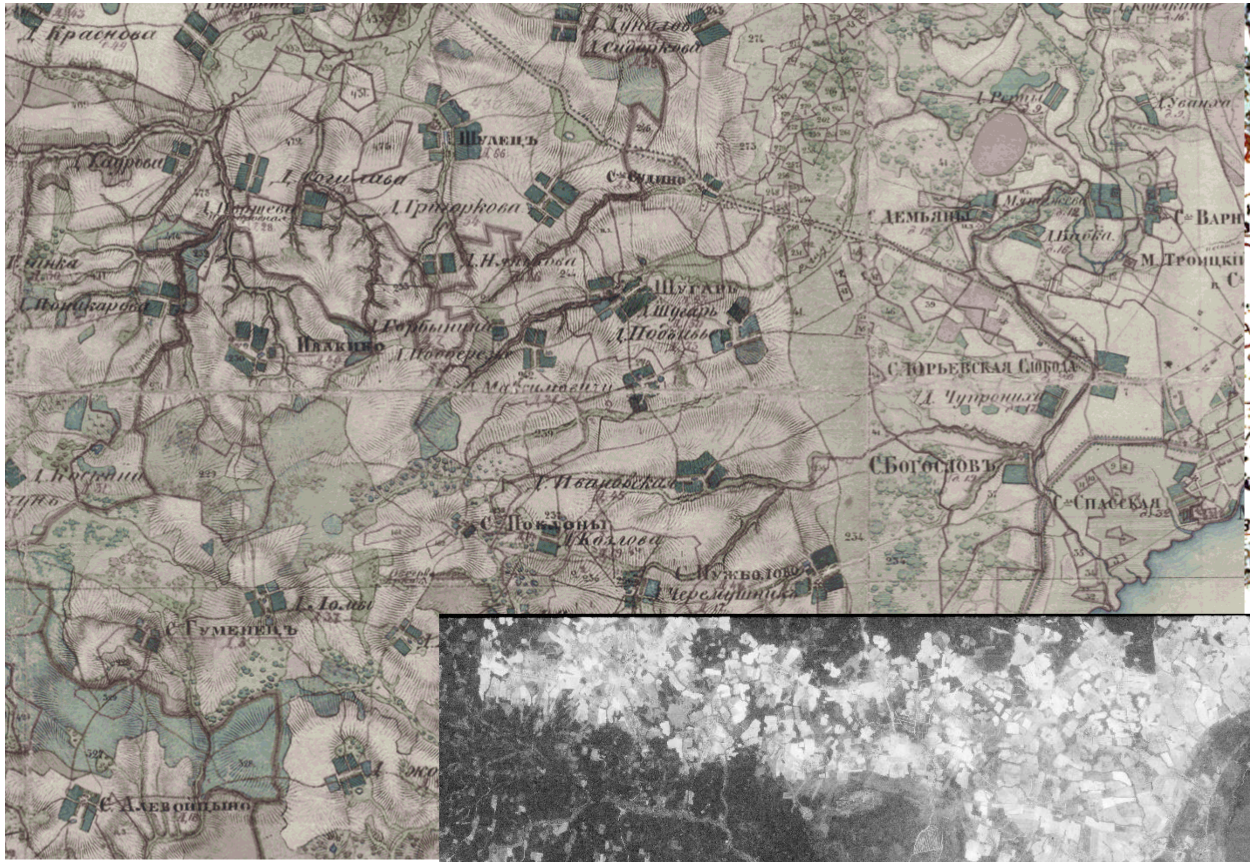


The Puzbol Gully catchment sediment connectivity index as proposed by Cavalli et al. (2013), estimated using the stand-alone application (SedInConnect 1.0) (Cavalli et al, 2014) for DEM with 5 m cell and W_{RI} estimated for the 5 cells moving window.

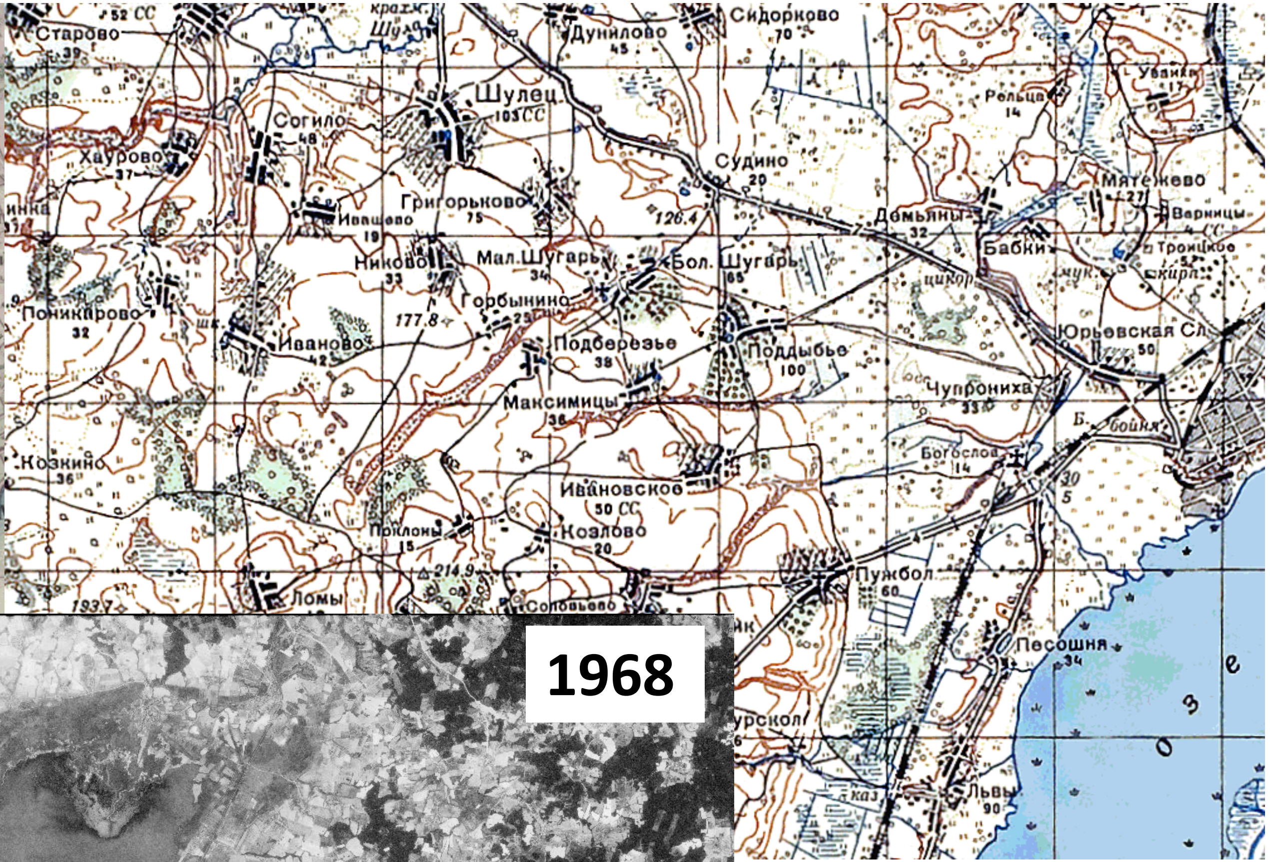
Research Perspectives 3

Recently obtained potential sources of information for the last ≈200 land use change mapping include topographic maps (1857, 1941, 1984) and Corona Satellite Images (1960s-70s):

1857



1941



Conclusions

Natural exposures in banks of active gullies illustrate the facial variability of the Holocene deposits including infilled and buried gully incisions with lenses of gully alluvium and polycyclic pedolithosediments produced by natural (most likely, wildfire-induced) and/or agrogenic hillslope water erosion deposits. Surface geology of closed depressions within the interfluvial areas of the catchment is dominated by lake and slope deposits while soil formation and erosion in those has been rather limited during the entire Holocene to a series of small local slope and fluvial incision-infill events.

A set of middle Holocene dates (between 5100-5700 ^{14}C yrs BP), obtained by analyzing total organic carbon from organic-accumulative layers of buried soils, fragments of relic humic horizons of the modern surface soils as well as some lake gyttja and peat layers, represents strong evidence of the synchronous phase of landscape stabilization in both upper and lower parts of the Puzhbol catchment accompanied by active infilling of small erosion cuts in its middle part.

Forest fires were most likely the principal driver of geomorphic dynamics, soil profile transformation and general landscape modification within the study area during most of the Holocene. Their frequencies and effects on soils and geomorphic systems is yet to be estimated. It can however be suggested that there were at least two episodes with increased frequencies of forest fires, at transition from middle to late Holocene (4600-5600 ^{14}C years BP) and during the last pre-anthropogenic phase of the late Holocene (1000-1500 14C years BP). These dates coincide well with information obtained for other sites in the European Russia (Panin et al., 2009).

Acknowledgments

Research was supported by Russian Science Foundation project 19-77-10061 in part of field work organization and morphological investigation, project 18-77-00083 in part of instrumental radiocarbon age measurement and GA AAAA-A16-11632810089-5 in part of lithological research using Fritsch Analysette Nanotek 22 NanoTec plus with wet dispersion unit purchased by the Department of Geomorphology and Paleogeography within the implementation of MSU development program.