Lateral interaction of local geosystems of outwash valley landscapes of the Lower Vyatka

A S Matushkin$^1$ and A M Prokashev$^{1,2}$

$^1$Vyatka State University, 36, Moskovskaya Str., Kirov, 610000, Russia
$^2$Vyatka State Agricultural Academy, 133, Oktyabrsky Ave., Kirov, 610000, Russia

E-mail: as_matushkin@vyatsu.ru

Abstract. The paper presents the results of the analysis of lateral interaction of outwash valley landscapes on mesorelief slopes in various parts of the Medvedsky Pine Forest Nature Sanctuary in the lower Vyatka valley. The baseline data were the results of the authors’ field and laboratory analytical studies of more than 120 landscape facies. These elementary landscapes occupy various geomorphological stages in the relief: I, II and III terraces above the floodplain as well as a strip of alluvial glaciofluvial deposits which graduates to the slope of the river valley. The mesorelief within each of these stages is also heterogeneous: it includes aeolian dunes and knobs, interdunal and interknob basins, karst basins and sub-horizontal surfaces. Three models of slope geosystems of the outwash valley are presented: ancient aeolian, marsh and karst. An original method for evaluating the strength of lateral interaction between certain units of slope geosystems based on the degree of difference in their states is proposed.

1. Introduction

Landscapes on light – sandy – deposits within the Eastern part of Europe (“the low-density forests”) have been of great geoecological significance recently. These landscapes, on the one hand, were not subject to active anthropogenic transformation, and, on the other hand, were not sufficiently studied due to their low-fertility soils. Currently, most of these territories are occupied by pine forests; they serve as elements of the ecological framework and need protection and comprehensive study. The Eastern woodlands of the Russian plain are considered to be the least studied in terms of landscape. The structures of landscapes and soil cover have been studied since 2008 on the left bank of the lower Vyatka valley (the Volga basin), on the territory of the Medvedsky Pine Forest Nature Sanctuary (Nolinsky district of the Kirov region).

In particular, it was found that the main factor of differentiation of landscape facies is mesorelief. However, a number of questions still arise about the nature of horizontal connections between certain local geosystems of the outwash valley landscape: what is their strength and what does it depend on? To find answers, we used the landscape catenae method. One catena can contain geosystems of various hierarchical ranks (for intra-landscape catenae – from facies to terrain) which follow each other down the slope and are connected by lateral (horizontal) connections. Most research, both in Russia and in other countries, concerns the study of soil catenae [1–5], and there is much less work on the analysis of lateral connections of landscapes [6–8]. Moreover, catenae are isolated particularly on
heavy rocks. Water-resistant properties of clays and loams limit the vertical movement of water and substances dissolved in it, but, at the same time, strengthen the lateral material energy connections.

Our task was to find out how strongly the mesorelief affects the lateral connections of local geosystems under the conditions of deep sands, shallow sands and sands with a high groundwater level. For this purpose, the field landscape studies were conducted on 28 slopes in various parts of the Medvedsky Pine Forest – with the dominant ancient aeolian, marsh and karst landscapes. Each catena depending on its position in the terrain and the migration of substances was divided into sets (links) which are located down the slope as follows: eluvial (EL), transeluvial (TEL), transaccumulative (TAC), superaquatic (SA) and sub-aquatic (SBA).

At the same time, the catenae with incomplete coupling may lack one or more sets. Within the catenary sets, landscape facies of the corresponding type are located. The strength of the lateral interaction was estimated between the facies located in the adjacent sets of the same catena. Only qualitatively dissimilar elements of any geosystem can exchange matter, energy and information with each other; thus, the more different the states of the adjacent facies are, the stronger their connection should be. The “state” of any facie stands for the features which are the basis for facies differentiation, namely: 1) position in the terrain; 2) soil difference; 3) plant association.

The position in the terrain was not taken into account when assessing the strength of the lateral interaction because the adjacent facies of different types along the catena line will always differ by one unit: e.g., the eluvial facie occupies the top of the dune, and the underlying neighboring transeluvial facie occupies the upper part of the slope, etc. Theoretically, soils can be represented by a single difference or they can differ at the unit level: e.g., peat gleic podzols (the “alfelhumus soils” unit) below the catena profile can be adjacent to eutric histosols (the “peat soils” unit).

The plant association of the adjacent facies may coincide or may be different even at the type level: e.g., forest vegetation may graduate into swamp vegetation. To quantify the similarity/difference of landscape facies, the highest classification level of soil and vegetation was used where the following difference was shown: from 1 – the soils differ by the unit (vegetation – by type), to 6 – there are no classification differences. Each level was assigned a soil difference score (Bs) and a vegetation difference score (Bv): from 5 (there is a difference at level 1) to 0 (level 6) (Table 1).

Table 1. Point estimation of the degree of difference between soil differences and plant associations depending on the classification level

| Soil differences | Plant associations |
|------------------|--------------------|
| Level            | Score (Bs)         | Level            | Score (Bv) |
| 1 unit           | 5                  | vegetation type | 5           |
| 2 type           | 4                  | I arborescent stratum (dominant rock) | 4 |
| 3 subtype        | 3                  | I arborescent stratum (co-dominant rock) | 3 |
| 4 species        | 2                  | ground cover (dominant species) | 2 |
| 5 variety        | 1                  | ground cover (co-dominant species) | 1 |
| 6 no differences | 0                  | no differences  | 0           |

The strength of the lateral interaction of the adjacent geosystems along the catena profile was estimated using the $F_{lat}$ indicator:

$$F_{lat} = Bs + Bv$$

Theoretically, the $F_{lat}$ value can take values from 0 (there is no connection between the geosystems) up to 10 (maximum interaction strength). The $F_{lat}$ indicator was calculated for the boundaries of EL/TEL, TEL/TAC, TAC/SA catenary sets of the individual catenae. The strength of the lateral interaction at the line between SA/SBA land and water landscapes was not specifically evaluated since the catenae in question did not end in a water object. However, it is obvious that the $F_{lat}$ value at this line will be the maximum in all cases. We suggest using the following scale for the $F_{lat}$ indicator qualitative evaluation: $0 \leq F_{lat} \leq 3$ – weak interaction; $3 < F_{lat} \leq 7$ – average interaction strength;
7 < \( F_{lat} \leq 10 \) – strong interaction. In addition to the individual \( F_{lat} \) values, the average values of this indicator were calculated for each type of catenary link boundaries within ancient aeolian, marsh, and karst landscapes:

\[
\bar{F}_{lat} = \frac{\sum F_{lat}}{N}
\]

where \( N \) is the number of catenae for which the values of individual \( F_{lat} \) indicators were summed.

2. Results and discussion

As a result of the analysis of the structure of slope geosystems and the strength of the lateral interactions between them, we can offer three models of landscape catenae of the outwash valley of the Medvedsky Pine Forest: ancient aeolian, marsh and karst (Fig. 1).

The ancient aeolian catenae (type A) are typical of the terraces above the floodplain of the Vyatka River and the area of alluvial glaciofluvial sand deposits at the transition to the slope of the river valley. In addition to the Medvedsky Pine Forest, similar catenae are described by the authors in the landscape of the Belaevsky Pine Forest on I terraces above the floodplain of the Vyatka river, 57 km upstream [9].

However, in the Medvedsky Pine Forest, in particular, the ancient aeolian catenae occupy a considerable area and are represented by various types depending on the thickness of the sand deposit. In the marginal part of thin alluvial glaciofluvial deposits (subtype A3), the aeolian mesorelief is formed by small knobs and single rectilinear transverse dunes with a relative height of up to 2 m with depressions between them. On III terraces above the floodplain of the Vyatka river (subtype A2), the ancient aeluvial sands are thicker. In the central part of the Medvedsky Pine Forest, under the influence of winds from opposite directions (south-east and north-west), circular dunes with a diameter of up to 120 m with deep deflation basins in the center were formed. The height of these dunes is up to 5 m, and the asymmetry of the slopes is clearly seen: the inner slope facing the basin is steep (25–30°), and the outer slope is more gentle (15–20°).

The ancient aeolian catenae on II terraces above the floodplain (subtype A1) are the most common in the Medvedsky landscape. The ancient alluvial sand drift is the thickest here – up to 20–30 m or more. This allowed the formation of high dunes (up to 10 m or more). A characteristic feature of the topography of this part of the landscape is the presence of long dune ridges (up to 500 m long) formed at the confluence of certain dunes. These ridges extend parallel to each other, usually in the north-eastern direction. In some cases, neighboring ridges are connected by relatively low bridges (2–3 m high) forming a kind of a cellular relief. The interstitial basins are quite large; they have an 8-shaped shape. The dunes forming this subtype of ancient aeolian catenae are characterized by the slope asymmetry (as in subtype 2).

Local geosystems on light sandy sandy-loam deposits and geosystems with a deep position of the water table are associated by the ancient aeolian catenae. Therefore, the vertical migration of water and solutes significantly prevails over the horizontal migration. These catenae have incomplete coupling and usually consist of only two sets: the EL set – on the tops of aeolian landforms, and the TEL set – on slopes and even in most basins where active vertical migration is arranged by good drainage. Rarely, the TAC set appears in the composition of these catenae. The differences in soil and vegetation in the catenae profile are poorly defined. In some cases, landscape differentiation is associated not with the position of the facies in the mesorelief but with the presence or absence of “windows” in the forest canopy.

The EL set occupies the peak facies on the superficial haplic sandy podzols (Po1Hs). The vegetation of these facies is represented by various pine trees (Nmed-14, 40, 67), and quite often there are lichen pine forests (Nmed-18, 21) and green moss lichen (Nmed-81, 84). Sod podzols are extremely rare (Nmed-15 under secondary birch forest). The TEL set is of maximum length in the composition of the ancient aeolian catenae. It includes the slopes and most of the basins of the aeolian terrain. There are both superficial and small (Po2Hs) haplic sandy podzols in the set. Moreover, the
share of Po₂ increases when moving down the catena profile. They are common, in particular, in the rock-basin land types (Nmed-96). In addition, in these locations, the illuvial ferruginous podzols are frequently replaced by the small carbic sandy (Po₂Cs) podzols. The reason for the morphological strengthening of the podzolic process and the illuviation of humus in the lower positions of the relief is a slight increase in soil moisture due to sinter moisture. The TAC set is rare. It is common in the ancient aeolian catenae of subtype A3 occupying interknob basins of the relief there. The close location of original limestones (0.4 m at the Nmed-11 facie) provides a relative richness of soils and hygro-mesophytic ecological conditions.

However, due to the fractured limestone, the facies are not waterlogged. Po₂Hs are the soils of this set, and the vegetation cover is dominated by pine-birch blueberry dead-cover spruce. In addition, the TAC set was found in the catenae of subtype A2 in the rock-basin land types (Nmed-20 facies, 86, 90). They have a relatively high accumulation of organic and mineral colloids in the soil due to the gain from the upper catenae positions as well. The soils of these land types are carbid sod podzols (SPoC) and, in some cases (Nmed-20), sandy loam soils. Dense underlying rocks are relatively shallow here (at the point of Nmed-86, they were opened by manual drilling at the level of 3.2 m). The plant associations are diverse: they vary from green moss pine forests (Nmed-20) to pine aspen green moss dead-cover forests with spruce (Nmed-86, 90).

The strength of the lateral interactions was studied within 20 ancient aeolian catenae. The average \( \bar{F}_{\text{lat}} \) (EL/TEL) value is small. It was 2.8 with a spread of individual \( \bar{F}_{\text{lat}} \) (EL/TEL) indicators from 0 to 6. The only catena with the highest \( \bar{F}_{\text{lat}} \) value (via Nmed-7 facies – 6 – 5) belongs to subtype A3 with close bedrock bedding. The TAC set was detected only in 6 catenae. The strength of the lateral interaction down the profile of the ancient aeolian catenae increases. The average \( \bar{F}_{\text{lat}} \) (TEL/TAC) value was 6.2, which indicates horizontal connections of average strength.
The swamp mesocatenae (type S) include interdunal basins where the groundwater comes close to the surface. It is mainly typical of the selvage of II terraces above the floodplain of the Vyatka river at the altitudes of 88–96 m above sea level. These catenae, in addition to the proper interdunal depressions, also occupy the surrounding slopes of the dunes and consist of four sets: EL, TEL, TAC, SA.

The two upper sets are almost identical in facie composition and other features to the corresponding sets of the ancient aeolian catenae. The $F_{\text{lat}}$ (EL/TEL) value based on the analysis of four marsh catenae was 4.3.

The TAC set includes facies of the lower parts of the dune slopes when they graduate into sedge swamps. The TEL/TAC border is characterized by the average and high strength of the lateral interactions. The $F_{\text{lat}}$ (TEL/TAC) value was 7.0.

The SA set of the marsh catenae includes waterlogged facies of interdunal peatlands. These locations collect water, mineral and organic compounds from the surrounding ancient aeolian complexes and are characterized by the highest groundwater level – 50–110 cm from the surface. The vegetation is represented by reed, sedge and sedge-sphagnum swamps on peat eutric typical and humic soils. Sedge swamps are most typical of these locations (Nmed-69, 76, 100). The inflow of groundwater, rich in nutrients, provides the hygrophytic composition of the vegetation of these facies as well as the dominance of the megatrofic plant – beaked sedge ($Carex rostrala$). In some cases, there is a more demanding megatrofic plant – reed ($Phragmites australis$). Interestingly enough, typical oligotrophic plants – sphagnum ($Sphagnum$), cranberry ($Oxycoccus palustris$), sundew ($Drosera rotundifolia$), scheuchzeria ($Scheuchzeria palustris$) – in sedge-sphagnum associations (Nmed-109) can also coexist with these species. They usually occupy a slightly higher location within the set (+0.5 m) and are drained by underlying facies. The elements of mineral nutrition migrate into them due to microcatenary interactions. The pea of such sedge-sphagnum swamps has a high acidity (pH = 4) and a weak degree of decomposition (OM = 90 %). According to their position in the mesorelief, such facies are only conditionally can be referred to swampy lowlands. Strong lateral relationships are observed at the TAC/SA border. The $F_{\text{lat}}$ (TAC/SA) value amounted to 9.7.

The karst catenae (type K) occur on II and III terraces above the floodplain of the Vyatka river as well as on alluvial glaciofluvial deposits on the left banks of the Yurtik and Klyuka rivers (left tributaries of the Vyatka). Karst in the Medvedsky landscape is mainly represented by two types of basins – conical and cup-shaped – which differ in their shape and age. Conical basins prevail where the ratio of depth (h) and upper diameter (d) is within 1/5. Among them, there are young basins with symmetrical sides and a small base. They contain the catenae of subtype K1. In addition, among the conical basins with a similar h/d ratio, there are older ones with asymmetric slopes and an expanded flat peaty bottom. The catenae of subtype K2 were studied inside these basins. Many conical basins are characterized by the presence of a small daughter basin in the immediate vicinity of the main one. They are separated by a narrow bridge that disappears as the basins grow which leads to the formation of karst basins with transverse thresholds on the bottoms. The oldest basins have a cup shape with relatively gentle sides and an extensive peaty bottom. The h/d ratio of such basins is from 1/5 to 1/10. The catenae of subtype K3 are located inside the cup-shaped basins. The evolution of the karst catenae...
is subject to changes in the shape of basins and proceeds as follows: 1) subtype K1 – 2) subtype K2 – 3) subtype K3. In the same direction, as the carbonates leach, the absolute height of the basin bottoms decreases: 1) 107.15 m above sea level – 2) 101.30 m above sea level – 3) 100.75 m above sea level. The thick cover of the sand deposits on most of the Medvedsky Pine Forest considerably slows down this evolution process; thus, conical basins prevail in the landscape.

The variety of catenary sets is quite representative. From top to bottom along the sinkhole profile, EL, TEL and SA sets usually replace each other. In some old catenae (subtypes K2 and K3), a small TAC set is present in the lower parts of the slopes. The end SBA set (aquascape) is as a rule absent, but in some cases it is occupied by a karst lake.

The EL set in all the subtypes of the karst catenae is formed by peak facies with atmospheric moisture and the dominant birch pine forests on Po$_1$Hs. The peak facies on thick sands have little effect on the lower-lying complexes. Good drainage causes soil desiccation and a high projective cover of xero-mesophytes (primarily cranberry).

The TEL set is formed by slope sub-land types. In young karst sinkholes, the steepness of the slopes is up to 40°. The set facies are birch pine with a small admixture of spruce in the forest stand on Po$_1$Hs (Nmed-123) or Po$_2$Cs (Nmed-120). In such steeply sloping terrain locations, due to the ablation of part of the sand material, the original carbonate rocks are located closest to the surface (Fig. 1). Due to this, the soil moisture is higher; thus, the presence of podzol is morphologically stronger, and in the grass suffructicose layer, hygro-mesophytes, primarily blueberries, prevail. The shallow position of the bedrock and the influx of mineral and organic colloids from the upper positions contribute to an increase in the value of spruce in the forest stand. This is characteristic, in particular, of the lower parts of the slopes. In the cup-shaped karst sinkholes (subtype K3), the upper parts of the slopes are usually flat, therefore, their soils, similar to the peak facies, are represented by Po$_1$Hs (Nmed-113). The strength of interactions of the upper sets $F_{lat}$ (EL/TEL) in all the subtypes of karst catenae is average and amounts to 4.3, which corresponds to the same indicator for marsh catenae.

The TAC set occupies small areas on the relatively flat (5–15°) lower parts of the slopes of karst landforms with atmospheric ground sinter moisture. Hydromorphism and trophicity of facies increase in the series K1–K2–K3. In the catenae of subtype K1, the TAC set is formed on the PoC, and in subtype K2 – on SPoC (Nmed-119). Humus substances of the illuvial horizon are partly sinter from the overlying facies. The improved conditions of mineral nutrition and increased humus content contribute to the presence of spruce in the forest stand as well as the pea vine (Lathyrus vernus), goutweed (Aegopodium podagraria) and other megatrophic plants in the grass suffructicous layer. Due to the soil and sinter components in the moistening of the set, pine is replaced by birch in the forest stand. The grass suffructicous layer of the set becomes meso-hygrophytic due to the high projective cover of wood horsetail (10 %).

An even more hydromorphic version of the TAC set is found in the catenae of subtype K3 of old cup-shaped karst basins. There are sedge swamps on small gleysic peat podzols (GPpo) (Nmed-111). These facies are under two-way influence: the upper sets of the catena provide water inflow, and the lower ones expand their areas up the slope due to the expansion of hygrophytic sedge phytocenoses. In addition to hygrophytic plants, there are also mesophytic plant groups typical of transit sets. The variety of environmental conditions and high intensity of substance and energy exchange make it possible to classify the TAC set as a landscape ecotone. This is also confirmed by the high value of the lateral connection strength $F_{lat}$ (TEL/TAC) that is 8.0, which is higher than the same value at this border in the ancient aeolian and marsh catenae.

The SA set of K2 and K3 karst catenae occupies the bottoms of deep basin with swamps, as a rule, on eutric histosols (Eh$^-$. In the catenae of subtype K1, the set soils are GPpo (Nmed-125). These locations are characterized by difficult drainage and strong influence of overlying facies – due to the influx of water, organic and mineral compounds. In old basins, prolonged waterlogging leads to the formation of a thick layer of slightly decomposed acidic peat. The vegetation cover of the set consists almost entirely of hygrophytes – sedges – beaked and slender (Carex lasiocarpa), ostrich fern (Matteuccia struthiopteris), wild calla (Calla palustris), sphagnum, hair moss (Polytrichum
commune), etc. Mesophytes play a significant role only in the $K1$ catenae on peat podzols. Due to the lower position of the set, organic and mineral compounds are accumulated. It is no coincidence that the hygrophytes that form the background of the vegetation cover of the bottoms are also usually megatrophs. At the TAC/SA border of the karst catenae, strong lateral interactions occur ($\text{F}_{\text{lat}}$ (TAC/SA) = 8.7) although somewhat less intense than in the marsh catenae ($\text{F}_{\text{lat}}$ (TAC/SA) = 9.7).

3. Conclusion

Therefore, the lateral interaction of local geosystems of valley outwash landscapes is complex and ambiguous. The strength of this interaction increases down the profile of landscape catenae and when the thickness of the sand deposit decreases and the water table rises. A different combination of these factors as well as the features of the forms and genesis of the valley outwash mesorelief allowed us to identify three types and six subtypes of landscape catenae with their own variety, structure of sets and the strength of lateral interactions between them. The most simple are the ancient aeolian landscape catenae which consist of two upper sets and are common in the central part of the Medvedsky outwash valley (subtype $A1$).

The lateral interaction here can be called conditional. Facie differentiation in such eluvial positions is usually associated not with catenary interactions but with different light conditions under shelterwood of the pine stand. Towards the periphery of the ancient aeolian landscape of the Medvedsky Pine Forest with a decrease in the thickness of light sand deposits (subtypes $A2$ and $A3$), the set of catenary links increases to 3, facie differentiation and horizontal interaction are enhanced. The marsh catenae ($S$) consist of four links with principally different strength of lateral connections: if their character is almost similar to type $A$ between the two upper links, the interaction of the lower TAC/SA sets is the strongest in the Medvedsky landscape.

The karst catenae (type $K$) in some cases (the presence of a karst lake) may have the most complete variety of five sets. These catenae are divided into three subtypes depending on the evolution stage of mesoforns of the karst relief. In the $K1$–$K2$–$K3$ range, the age, size and depth of the basins as well as the set of catenary links and the strength of lateral interactions between them increase.

However, over time, with significant flattening of the karst terrain, the strength of horizontal redistribution of matter and energy within the catena may decrease. In general, the models are arranged as follows by increasing the overall average values of the lateral interaction strength: $A$ (3.6) – $K$ (6.8) – $S$ (7.0). As can be seen, the value of the karst catenae is slightly lower than that of the marsh catenae in this indicator, which is explained by the presence of young basins in the landscape.

References

[1] Samonova O A and Aseyeva E N 2013 Distribution of metals in particle size fractions in soils of two forested catenas (Smolensk–Moscow Upland) Geography, Environment, Sustainability 6(2) 28–33
[2] Owliaie H 2014 Soil genesis along a catena in Southwestern Iran: a micromorphological approach Arch. of Agron. and Soil Sci. 60(4) 471–86
[3] Jauss V, Lehmann J, Johnson M, Krull E and Daub M 2015 Pyrogenic carbon controls across a soil catena in the Pacific Northwest Catena 124 53–9
[4] Pasquini A I, Campodonico V A, Rouzaut S and Giampaoli V 2017 Geochemistry of a soil catena developed from loess deposits in a semiarid environment, Sierra Chica De Córdoba, Central Argentina Geoderma 295 53–68
[5] Fischer T and Veste M 2018 Carbon cycling of biological soil crusts mirrors ecological maturity along a Central European Inland Dune Catena Catena 160 68–75
[6] Berezhnov A V and Berezhnaya T V 2004 Landscape-ecological district of the Voronezh Region and their catenas Proc. of Voronezh State Univer. Ser. Geogr. Geoeocol. 1 110–7
[7] Malinowska E and Szumacher I 2013 Application of the catena concept in studies of landscape system dynamics Miscellanea Geogr. 17(4) 42–9
[8] Kapitalchuk I P, Sheshnitsan T L, Sheshnitsan S S and Kapitalchuk M V 2018 Migration of
manganese, zinc, copper and molybden in landscape-geochemical catena of the Lower Dnester Valley South of Russ.: Ecol., Development 13(2) 96–112

[9] Chepurnov R R, Perestoronina O N, Khlynov A Y and Prokashev A M 2016 Landscape structure of the outwash plain in the natural monument named Belaevskiy Bor In the World of Sci. Discover. 3(2) 34–46