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Monitoring of channel processes on the interfluve between the Kama and the Vyatka rivers

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Abstract Results of a survey of lateral channel shift from 54 control sections of different rivers that flow across various landscapes of Udmurtia are presented and discussed. The intensity of bank downcutting is controlled by a number of natural factors. Human economic activity in the drainage basin also exerts an important influence on the pattern of channel migration.

Key words bank erosion; channel morphological type; channel shift; factors of channel processes; meandering; monitoring; Udmurt Republic

INTRODUCTION AND STUDY AREA

A network of numerous rivers belonging to the Kama and Vyatka river basins, dissect the plain territory of the Udmurt Respublic (UR). The most widespread type of river channel morphology is meandering. A survey of morphometrical and morphological characteristics of river channels has been carried out using published topographic maps (scale 1:25 000, 1:50 000, 1:100 000) to distinguish the type of meander. Rivers of Hortonian orders 2–4 have been chosen for this survey. The main aim of the work presented is a geographical analysis of morphodynamic river channel type distribution within the UR and determination of channel lateral migration rates (Fig. 1). Influence of natural and environmental factors on river channel dynamics is also discussed.

Two main morphological types of river channels are distinguished within the region according to their pattern and tendency of lateral shift: relatively straight and meandering channels (Chalov *et al.*, 1998). Relatively straight channels dominate the upper reaches of rivers and comprise up to 25% of the total river length in the Vala basin and 38% in the Izh basin. Channel gradients of these river sections have maximum values of 0.009–0.01, coefficient of sinuosity is minimum.

Free meanders (not confined by bedrock slopes) prevail among meandering channels. It is well known that meanders pass certain stages in the process of their development. Each stage of development differs in intensity and direction of lateral deformation of the meander, kinematic flow structure and hydraulic characteristics. There are five types of meandering channels identified on the UR rivers (Table 1): segmented gradual meanders ($1.15 < L/l < 1.40$), segmented developed ($1.40 < L/l < 1.70$), segmented steep ($1.70 < L/l < 2.00$), loop-shaped ($L/l > 2.00$), cut-off ($1.50 < L/l < 2.00$), where L/l is a ratio of channel length to meander step (sinuosity coefficient).

The most widespread are segmented meanders in which downstream shift dominates. On average these occupy about 63% of the total channel length (from 55% in the Kilmez River basin to 71% in the Toyma River basin). Segmented meanders exhibit different stages of development which is evidence for active transformation of river channel planform as a whole. All three main stages in the development of segmented meanders, from gradual to

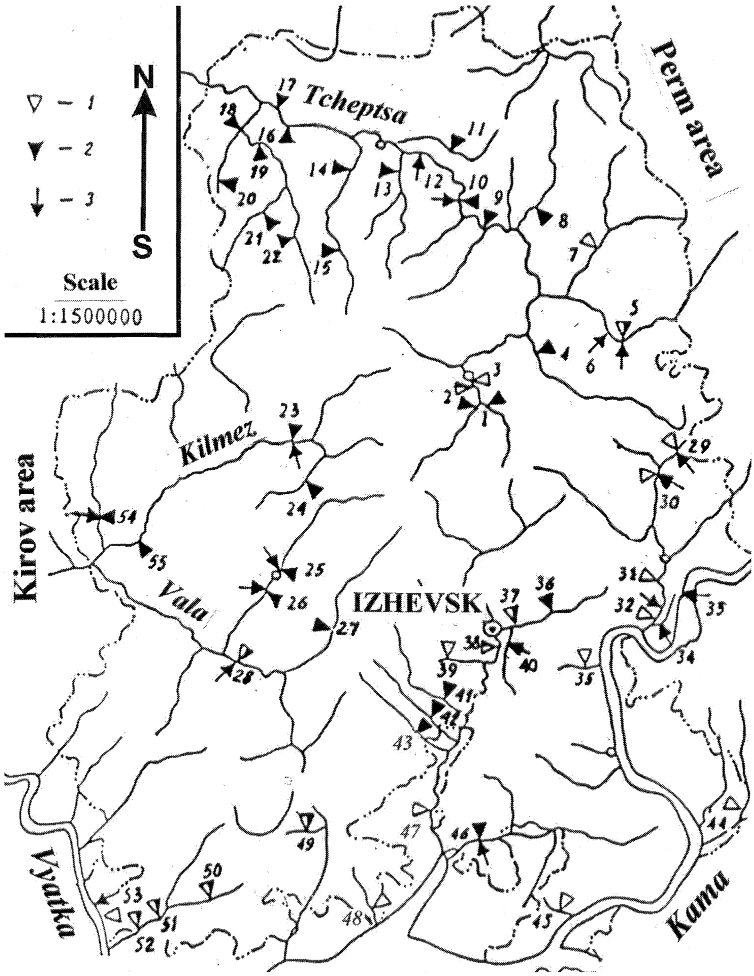

Fig. 1 Schematic of bank erosion monitoring points locations on rivers of the UR. (1) marks and reference points installed in 1999; (2) fixed marks and control points installed in 2000; (3) tacheometric survey of eroded bank sections.

Table 1 Distribution of morphodynamic channel types in different river basins of the UR (%).

Morphodynamic channel type	Tcheptsa	Vala	Kilmez	Siva	Izh	Toyma and the left Vyatka tributary	The right Kama tributary
1. Relatively straight	28	25	32	35	38	28	32
2. Free meandering	72	75	68	65	62	72	68
(a) gradual segmented meanders	29	53	29	46	37	48	60
(b) developed segmented meanders	14	11	23	9	17	19	6
(c) steep segmented meander	13	–	3	4	4	4	2
(d) loop-shaped meander	12	6	10	4	2	1	–
(e) cut-off meanders	4	5	3	2	2	–	–

steep (Chalov *et al.*, 1998), are present at certain river reaches. The subsequent stages of meander development under different conditions are associated with either straightening of the river bed and formation of a cut-off meander, or with further curvature increase and transformation into a loop-shaped meander. For the latter, increase in meander belt dominates over downstream shift. Cut-off meanders occupy about 2–5% of the total river length of the UR, and loop-shaped meanders—10–12% in the basins of medium sized rivers and 1–4% in basins with smaller rivers.

Sinuosity and asymmetry coefficients have been calculated in order to determine more precisely morphodynamic channel type. The sinuosity coefficient (C_s) suggests that the predominant channel type is straight and gradual segmented meandering with the C_s value ranging from 1.1 to 1.4. The asymmetry coefficient for the river valley slopes was estimated as:

$$K = 1 - L_k / L_p$$

where L_k, length of steeper slope; L_p, length of more gradual slope.

The valleys of both large and medium rivers are characterized by sharp asymmetry of slopes. Within the territory of UR two main genetic types of asymmetry (planetary and climatic), and two secondary types (tectonic and hydrodynamical) are present. The spatial distribution of asymmetrical sections of river valleys is uneven. Within the UR, average value of asymmetry coefficient is 0.44. The number of symmetrical valley sections is 7.6% and sharply asymmetrical ones is 58.4%. From the south to the north there is an increase in the proportion of symmetrical valley sections from 5–7% to 19%. The number of sharp asymmetrical sections decreases accordingly from 50–55% to 35%.

THE STUDY METHODS AND RESULTS

Meandering channels actively develop in time and space, changing their planforms. The main causes of this are lateral channel deformations. Comparison of air photos taken in 1934 and 1987 (scale 1:10 000) has allowed us to estimate the rates of lateral channel migration for the Tcheptsa River and its main tributaries (Table 2). For the main river, average channel lateral shift in 53 years has been estimated at 55.3 m (maximum, 105 m; minimum, <10 m), giving an average bank downcutting rate of 1.02 m year^{-1}. On the tributaries of the Tcheptsa River, the channel deformation has been found to vary from 30 to 160 m, and the range of bank retreat rates are 0.30–0.90 m year^{-1}.

Since 1999, regular annual surveys of lateral channel shift have been carried out on some rivers of the UR in summer. For this purpose, about 300 fixed marks and control points

Table 2 Rates of systematic channel shifts in the Tcheptsa River basin during 1934–1987.

River basin	Number of sections	Maximum shift (m)	Minimum shift (m)	Average shift (m)	Average rate of shift (m year^{-1})
Tcheptsa	47	105	9	55.3	1.02
Loza	5	98	35	63.3	1.17
Ita	4	60	30	48.7	0.90
Lekma	14	100	10	22.8	0.42
Ubit	18	30	10	16.1	0.30
Sada	5	30	12	19.0	0.35
Sepitch	50	160	10	40.6	0.75

Table 3 Morphometric characteristics of studied rivers.

Groups of rivers	1	2	3
Length (km)	<25	25–100	>100
Channel width (m)	5–10	15–50	>50
Meander radius (km)	0.1–0.15	0.20–0.25	>0.7
Gradient (m km^{-1})	2–2.5	0.6–1.0	<0.2

have been installed on actively transforming sections (often on high flood plain levels). Repeated theodolit-tacheometrical surveys have been conducted on 30 sections annually. The river sections studied are rather diverse, with the intensity of channel processes differing greatly. This provided for classification of rivers into three groups according to their morphometry: 1, very small; 2, small; 3, medium and large (Table 3).

Values of annual bank retreat vary considerably. During 2003 average bank downcutting rate in the UR was 0.47 m $year^{-1}$. Rates were on average greatest in 2001 (Table 4). The greatest average annual rates of lateral channel shift of 1.2 to 3.0 m $year^{-1}$ took place on rivers of the third group, which are characterized by high discharges and flow velocity. The maximum annual rate of bank retreat occurred along river reaches where the channel is at least 5–10 m wide. For the second group of rivers, average rates of bank downcutting are between 0.4 and 0.7 m $year^{-1}$ with maximum rates of up to 2–3 m $year^{-1}$. For the streams of the first group, estimated values are lower: 0.1–0.3 m $year^{-1}$, though at certain points a shift of 1 m $year^{-1}$ and more has been observed.

The method of fixed marks and control points has its shortcoming: only certain points along actively retreating sections are studied and it is rather difficult to evaluate the whole process. More detailed investigation is possible by making systematic tacheometric surveys of entire channel sections. Conventional theodolits and, later, electronic tachometers have been used for carrying out geodetic surveys. The length of the survey sections ranged from 50–100 to 400–500 m.

Survey data processing has allowed us to create eroded bank plans. From these, not only average and maximum bank retreat rates, but also areas and volumes of erosion can be determined. To compare these, ratios of area and volume of eroded bank to the length of the certain section have been calculated and called the specific area and volumetric erosion rates. The greatest specific areas and volumetric rates of bank downcutting have also been observed on large rivers, varying from 0.4 to 0.8 m^2 m^{-1} and from 2.0 to 17.2 m^3 m^{-1} (Table 5). For smaller rivers specific erosion areas vary from 0.1 to 0.3 m^2 m^{-1} and specific volumes from 0.4 to 0.6 m^3 m^{-1}.

DISCUSSION

The data obtained for the last 4 years has allowed us to consider the dynamics of lateral channel shifts and make some conclusions about the influence of different factors. The major agent in the channel formation is water discharge. This is demonstrated by the higher correlation coefficients for the relationship between channel lateral shift and average annual water discharge (Table 6). Table 6 also shows that along with the discharge, other natural factors exert considerable influence in bank downcutting intensity. These are rock lithology, slope gradients, radius of meander curvature, soils and vegetation cover.

Table 4 Average annual rates of bank retreat of rivers of the UR for the period of 2000–2003.

Number	Rivers	Control section (settlement)	Average annual rates of bank retreat (m year^{-1}) 2000	2001	2002	2003
1	Loza	Kushya	–[1]	0.15	0.26	0.12
2	Nyas	Sundur	0.0	0.23	0.10	0.63
3	Loza	Loza	0.14	0.09	0.38	0.36
4	Ita	Zura	–	0.27	0.41	0.23
5	Tcheptsa	Debesy	0.48	0.44	0.44	0.52
6	Lyp	Sosnovy bor	0.43	0.19	0.24	0.24
7	Pysep	Bany	–	0.86	0.32	0.68
8	Tcheptsa	Kamenoe sadelye	–	1.80	–	1.2
9	Tcheptsa	Kozhilo	–	1.33	1.25	0.31
10	Varyzh	Keldikovo	–	0.42	0.32	0.29
11	Sepitch	Glazov	–	–	0.82	0.49
12	Ubyt	Tchura	–	0.34	0.13	0
13	Ubyt	Palagay	–	0.23	0.21	0.16
14	Tcheptsa	Yar	–	0.43	0.44	1.44
15	Tcheptsa	Dizmino	–	1.27	1.65	1.05
19	Lekma	Nizhny Ukan	–	0.16	0.07	0
20	Sada	Yur	–	0.17	0.10	0.05
21	Lema	Shamardan	–	0.10	0.05	0.08
22	Lekma	Potchinky	–	0.28	0.10	0.14
23	Kilmez	Goloviznin Yazok	–	2.24	1.43	0.56
24	Arlet	Tchibir-Zyunya	–	0.29	0.23	0.13
26	Uva	Uva-Tuklya	–	0.45	0.51	0.37
27	Nylga	Hilga	–	0.57	063	0.45
28	Vala	Makarovo	0.52	0.98	0.52	0.38
29	Bilibka	Shoner	0.10	0.34	0.10	0.16
30	Sharkan	Titovo	0.51	0.12	0.56	0.15
31	Siva	Gavrilovka	0.27	0.60	0.85	0.23
35	Golyanka	Goliany	0.38	0.20	0.25	0.3
36	Pozim	Kabanikha	0.44	0.05	0.12	0.28
37	Pozim	Pozim	–	0.10	0.10	0.27
38	Izh	Bolshaya Vehya	0.45	0.27	0.28	0.24
39	Ludzinka	Yusky	0.33	0.46	0.27	0.13
41	Agryzka	Bagrash-Bigra	–	–	0.92	3.15
42	Postolka	Postolsky	–	–	0.45	018
43	Bobinka	Abdes-Urdes	–	–	0.09	0.61
44	Piz	Novokreshenka	–	0.48	0.04	–
45	Kobylka	Klestovo	0.35	0.22	0.23	0.13
46	Kirikmas	Tavzyamal	–	0.55	0.18	0.72
47	Izh	Russkaya Sharshada	0.22	0.12	0.14	0.46
48	Varzinka	Yumyashur	–	0.15	0.11	0.2
49	Alnashka	Alnashy	–	0.19	0.21	0.15
50	Adamka	Grakhovo	0.20	0.25	0.40	0.15
51	Umyak	Pussky Kuyuk	0.52	0.45	0.18	0.15
52	Umyak	Bazhenikha	–	0.15	0.13	0.13
53	Vyatka	Krimskaya Sludka	3.25	3.97	4.53	3.0
54	Lumpun	Kharlamovskaya	–	–	–	0.16
55	Kilmez	Maliye Syumsy	–	–	–	0.65
Average total			0.48	0.54	0.50	0.47

[1] – indicate "not measured".

Table 5 Areas and volumes of bank retreat in rivers of the UR for the period of 2001–2002 year.

River	Control section (settlement)	Area (m^2) / specific area (m^2 m^{-1})		Volume (m^3) / specific volume (m^3 m^{-1})	
		2001	2002	2001	2002
Vyatka	Krimskaya Sludka	117.7/0.39	–	5107.7/17.2	–
Kilmez	GolovizninYazok	86.9/0.75	97.0/0.85	378.8/3.29	423.0/3.7
Tcheptsa	Lnozavod–1	170.0/0.41	43.5/021	884.0/2.2	226.2/1.10
Tcheptsa	Lnozavod–2	30.92/0.12	30.5/0.13	160.78/0.64	159.7/0.65
Tcheptsa	Adam–1	28.4/0.12	67.0/0.26	147.68/0.61	348.4/1.36
Tcheptsa	Adam–2	–	170.0/0.41	–	885.4/4.29
Tcheptsa	Debecy–1	17.84/0.27	24.0/0.18	1340.23/1.0	175.2/1.29
Tcheptsa	Debesy–2	–	44.0/0.21	–	168.5/0.81
Tcheptsa	Varny	–	37.0/0.19	–	208.0/1.08
Siva	Metlyaky–1	–	116.0/0.47	–	464.0/1.9
Siva	Metlyaky–2	16.9/0.16	46.5/0.61	67.5/0.67	186.0/2.5
Kirikmas	Tavzyamal–1	–	38.5/0.16	–	200.2/0.82
Kirikmas	Tavzyamal–2	15.84/0.08	21.5/0.10	82.37/0.41	179.4/0.82
Uva	Uva	11.74/0.13	17.8/0.18	44.5/0.49	68.2/0.71
Kama,res.	Berkuty	25.76/0.42	29.0/0.51	762.49/12.7	858.9/15.3
Kama,res.	Galevo	–	27.0/0.22	–	810.0/5.53
Sharkanka	Titovo–1	–	24.0/0.27	–	68.3/0.78
Sharkanka	Titovo–2	–	16.5/0.24	–	42.02/0.60
Sharkanka	Shoner	–	10.0/0.17	–	32.5/0.54
Vala	B.Volkovo	38.55/0.19	–	115.05/0.58	–
Bidvayka	Zavyalovo	–	12.0/0.08	–	31.9/0.22

Table 6 Coefficients of correlation between rate of bank retreat and different natural factors.

Groups of rivers	1	2	3
Water discharge	0.585	0.658	0.782
Stream gradient	0.577	0.451	0.758
Meander radius	0.687	0.381	0.812
Erosion stability	–0.622	–0.440	–0.690
Forest vegetation (% of basin area)	0.314	0.350	0.589

Intensity of erosion depends on such soil characteristics as resistance to erosion (bank strength) and permeability/infiltration capacity. Soil resistance to erosion has been determined using the approach proposed by Bastrakov (1990). It essentially involves measuring the impact of a single water jet with a known hydraulic power onto an undisturbed soil sample placed in a cylindrical steel container. Experiments were carried out on a specially designed apparatus in a laboratory.

Obtained values of resistance to erosion (R) characterize the ability of soil to withstand erosion. The values of R vary greatly from 3.15 to 15.5 Newton (N). Erosion stability depends mainly on the soil texture. Average index of R for sandy soils is 3.7 N; loamy-sandy soils, 4.3 N; medium-loamy, 6.6 N; and clayey-loamy, 10.0 N.

The relationship between erosion stability and bank retreat rates is separately determined for all three groups of streams by the calculation of the correlation coefficient. As expected, these are negatively correlated, i.e. the higher the erosion resistance, the lower is the lateral channel shift rate. This relationship is especially clear in the first and third groups of rivers: $r = -0.622$ (first group) and $r = -0.690$ (third group). For the most abundant second group of rivers this relationship is weaker ($r = -0.440$) because of the higher variability of both bank retreat rate and soil resistance to erosion (Table 6).

Channel gradient greatly influences the intensity of channel deformations and erosion. When the gradient is high, erosion and transportation capacity of flow increases. Calculated values of correlative ratio confirm this fact (Table 6). This linkage is especially clear for large rivers ($r = 0.758$). The values of the first and the second groups of rivers are lower ($r = 0.577$ and $r = 0.451$, respectively).

The value of the meander curvature radius also influences the rate of lateral erosion. The higher is the channel curvature, the higher is the flow velocity along the eroded concave bank of a meander. Circular currents directed from concave to convex meander bank are formed within the main flow, which intensify bank erosion significantly. This relationship is rather weak for the second group of rivers ($r = 0.381$). The relationship is closer for the first group of streams ($r = 0.687$) and the best for the large rivers of the third group ($r = 0.812$).

Another factor influencing the intensity of riverbank erosion is vegetation cover and in particular forest vegetation percentage (FVP). Values of FVP at control sections change from 10–20% in the southern part of the UR to 70% and more to the north. Calculated values of correlative ratio between the bank retreat rate and the FVP show that some relationship exists between them. However, as the linkage is rather weak then FVP does not play the main role in river channel deformation.

The present condition of river channels is also strongly influenced by the extent of anthropogenic activity in river valleys. Its degree and extent is very diverse, especially for large rivers. Small rivers dominate in the region of the UR, and the extent of human impact on their valleys is relatively low. On the other hand, such rivers react to natural and anthropogenic changes within their drainage basins more intensively and quickly.

Deforestation and intensive cultivation of the drainage basins result in delivering great amount of sediments to small river valleys and channels. It causes intensified deposition and siltation of channels. Earth dams are often constructed in small river valleys, in order to maintain water supply in summer months. During spring floods many such dams can be breached by intensive runoff, flow velocities increase greatly and erosion accelerates. For example, significant bank downcutting has been observed on the Agrizka River (the Izh River basin) in 2003 as a result of earthen dam breach. The maximum value of the bank retreat was more than 8 m in this instance.

Construction of some engineering structures, communication lines etc. on river banks and in channels also result in the process of channel regime changes. One of the oldest forms of local engineering effects to river channels is bridge construction. It usually causes flood capacity decrease, which results in the formation of hydraulic jump above the bridge (head wave is greatest at water conveying outlets of road embankments, crossing small rivers) and hydraulic fall below the bridge during floods. That increases specific water discharge and erosion intensity. Sharp changes of the channel morphology and intensification of lateral deformations can take place below the bridges. Some control sections give clear examples of the differences in channel deformation intensity upstream and downstream from bridges where bank retreat rates upstream of bridges are far lower (Table 7).

Table 7 Rates of bank retreat upstream and downstream from bridges (2003 year data).

River (settlement)	Average annual rate of bank retreat upstream from bridges (m $year^{-1}$)	Average annual rate of bank retreat downstream from bridges (m $year^{-1}$)
Ita (Zura)	0.10–0.15	0.25–0.40
Lyp (Sosnovy Bor)	0.01–0.10	0.50–0.90
Golianka (Golyany)	0.10–0.20	0.30–0.50
Ludzinka (Yusky)	0.05–0.10	0.30–0.40

During melioration activities, rivers serve as water receivers and transmitters, which increases their discharge. Such increase may not be visible at all for larger rivers, but is very a serious factor for smaller rivers and can sometimes cause very serious erosion where active incision of valley floors and active bank collapses take place. An example of such negative anthropogenic activity has been observed at the control section in the area of Nylga settlement (the Nylga River). A network of drainage ditches was constructed there, through which the flood plain water was diverted back into the channel. For this reason active development of meandering process, deformation of segmented meanders, high rate of lateral erosion (average bank retreat rate for 2003 is 0.45 m $year^{-1}$, maximum 1.15 m $year^{-1}$) has became characteristic for this river section.

Under the influence of anthropogenic factor, rivers can also negatively affect the life of people. Engineering structures, communications, residences can be damaged as a result of bank erosion. Valuable agricultural fields and forest areas can also be lost. The data obtained in this study will be used in the forecasting of hazardous situations along the rivers and streams of the UR.

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