Alluvial relief structure and bottom sediments of the lower Volga River

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Abstract The alluvial relief of the lower Volga River has a complicated hierarchical structure. This structure includes megaripples, three orders of dunes, two orders of bars, islands and meanders. The main channel of the Volga and its branch the Akhtuba, form a parallel-channel system. This complicated structure is one of the main characteristics of unconfined large rivers with a fine bed load.

Key words alluvial relief; bottom deposits; hierarchical structure; lower Volga River channel; sonar measurements

INTRODUCTION

Alluvial relief is characterized by a well-defined hierarchical structure (Sidorchuk, 1996; Alekseevskiy, 1998). The most complicated hierarchy can be observed at the unconfined reaches of the large rivers having sandy alluvium. The lower Volga River is one of the best examples of the high diversity and dynamics of alluvial features. The lower Volga valley in the Volgograd and Astrakhan' districts is well developed. Most settlements are situated along the river banks and changes in the river channel can cause environmental hazards. Sediment dynamics and river bank erosion lead to instability in hydro-technical constructions and cause sedimentation of water intakes and quays, and erosion around pipelines and bridges. These negative effects of the channel processes need to be considered in the planning and practice of the river valley development. Therefore the hydrological and morphological features of the lower Volga River channel require investigation.

METHODS OF INVESTIGATION

Investigations of the morphology and dynamics of the main lower Volga River channel and its distributaries along the section from Volgograd to Astrakhan' in the period 1995–2003 complemented significantly the existing information about fluvial processes, bottom sediment size and thickness. The bottom relief and alluvium characteristics were measured with a complex of hydro-sonar equipment (side-looking and profiler), designed in the Sonar Laboratory of the Institute of Oceanology, RAS, and the coordination of the survey was performed using a GPS system. Sonar measurements were interpreted using existing coring data (held by the Gidroproyekt and Soyusmorniiproyekt institutes) and analyses of bottom sediment particle size sampled during 1990–2003 (Korotaev & Ivanov, 2000). The observations covered the 520-km long section of the lower Volga River from Volgograd to Astrakhan' (Fig. 1(a)).

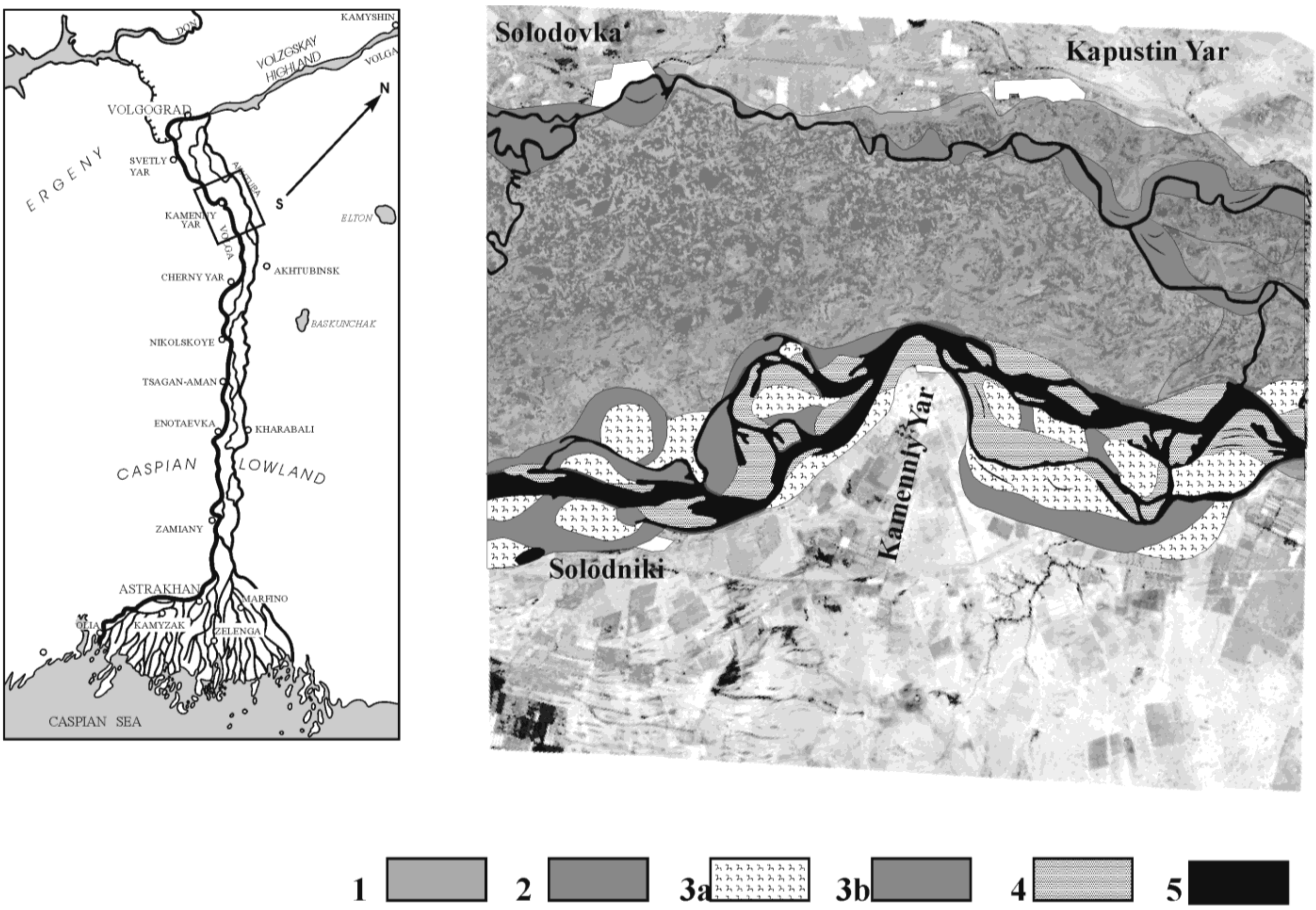

Fig. 1 The lower Volga River valley: (a) general view, and (b) main morphological features of the section near Kamenniy Yar. 1: high Volga-Akhtuba floodplain; 2: meandering belt of Akhtuba; 3: floodplain of the Volga River main channel (a: high surface, b: low channel remnants); 4: second order alternation and braid bars; 5: river channels and branches.

HYDROLOGICAL REGIME OF THE LOWER VOLGA RIVER

The lower Volga River is a typical lowland river with mean slope 0.031 m km^{-1}. The annual flow is 259 km^3 near Volgograd and 253 km^3 at the river outlet to the Caspian Sea. The lower Volga valley is situated in a semi-desert region with high evapotranspiration. The water regime of the Volga River was changed by the construction of a system of hydro-electric dams with large reservoirs. The lower Volga is mainly influenced by the Volgograd reservoir, constructed in 1959. The mean maximum discharge was reduced from 34 500 $m^3 s^{-1}$ before 1959 (with the extreme 51 900 $m^3 s^{-1}$ in 1926) to 26 800 $m^3 s^{-1}$ in 1959–1999 (with the extreme 34 100 $m^3 s^{-1}$ in 1979). The water regime regulation led to concentration of the water flow in the main river channel and abandonment of the small flood plain distributaries.

Bed load and suspended load deposition in the reservoirs led to significant decrease of the sediment input to the lower Volga River. In 1938–1953 the annual sediment load near Volgograd was 12×10^6 t, and it was 13×10^6 t at the delta head. Some increase of sediment load was observed along the lower Volga River channel due to local erosion. Sediment transport measurements in the Volgograd reservoir were terminated after reservoir construction, therefore comparative figures are available only for the delta head. Here the annual load decreased nearly two-fold to 7.9×10^6 t, the annual maximum load decreased from 3 900 to 2 100 kg s^{-1}, the mean annual suspended sediment concentration decreased from 56 to 34 g m^{-3}, and the annual maximum suspended sediment concentration decreased from 250 to 170 g m^{-3}.

CHANNEL BOTTOM DEPOSITS

Bottom deposits in the Volga River channel are only partly formed due to accumulation of suspended and wash load. These finer sediments (silty sand and silt) have accumulated on the surface of the Volga-Akhtuba floodplain and in the Volga River delta. The main source of bottom deposits is the transit and deposition of alluvial bed load. In the channel segment below the Volgograd reservoir dam the bed load and bottom deposits are represented by sand with median grain size 0.15–0.50 mm (Fig. 2). Collection and analysis of sediment samples shows two main lithological parts of the channel: (a) from Volgograd to Tsagan-Aman the most frequent deposits (~60% of the bottom area) are medium-sized sands with a median diameter 0.25–0.45 mm; (b) fine sand (0.1–0.25 mm) covers the main part of the channel bed between Tsagan-Aman and Astrakhan'. The coarsest material (median diameter 0.6–0.7 mm) is observed along the eroded bed rock valley sides.

Sonar profiler measurements show a mean thickness of 6–8 m of bottom alluvial deposits in the lower Volga River, and the actual thickness varies from 0 to 15 m. Along the eroded banks (mainly at concave meander loops) the channel bed is composed of marine clay and flood plain loams. This cohesive matter **[the marine clay? Yes, but in round brackets]** is quite often exposed in deep pools. Locally, about a third part of the channel bottom is not covered with alluvium.

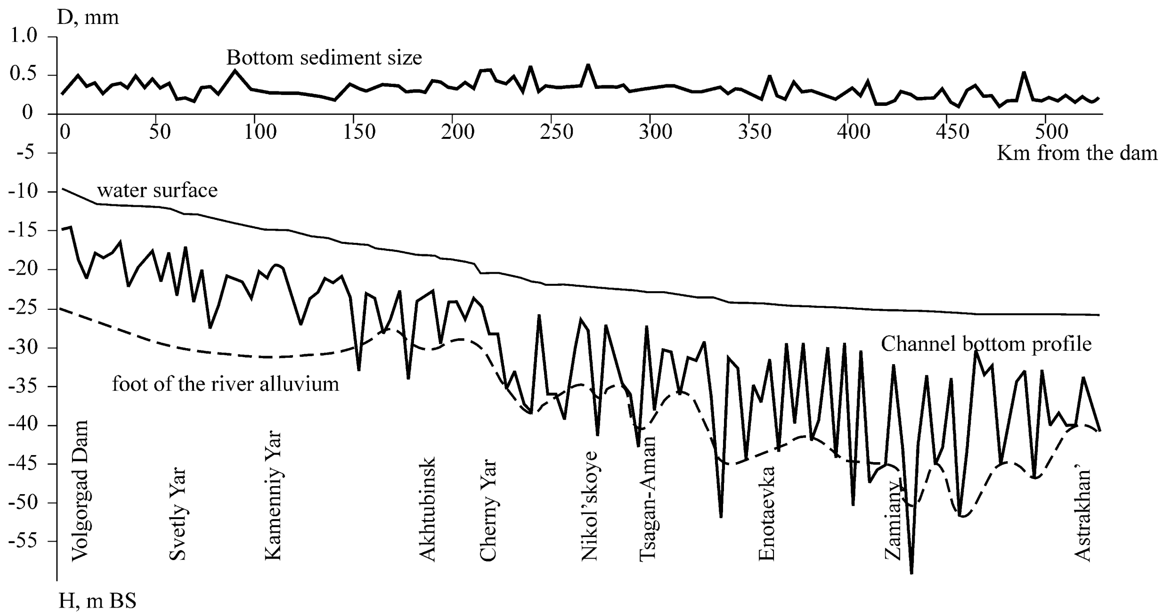

Fig. 2 Changes of the bottom sediment size and channel alluvium thickness along the lower Volga River channel.

RIVER CHANNEL MORPHOLOGY

The lower Volga River is characterized by two main channels: the Volga River main channel and the Akhtuba river branch, located respectively along the western and eastern borders of the valley floor. These two channels are divided by a broad flood plain and are connected by a complicated net of flood plain distributaries of different size.

The main channel has a mean width of 1.5 km between the flood plain banks and has a sinuous pattern with multiple secondary anabranches (local term is “volozhka”), divided by islands, covered by vegetation (Fig. 1(b)). These islands, of mean length 10–13 km, may be solid, and may be composite, consisting of several islands with dividing branches. Anabranches mainly occur in the upper part of the lower Volga River, whereas a single channel with well-shaped meanders is more common in the lowermost segment.

The Akhtuba branch has a mean width of 250 m and has a meandering pattern. The typical meander wavelength is 2 km. The Akhtuba flows parallel to the main channel of the Volga River for a distance of about 520 km, but only twice (near Akhtubinsk and Tsagan-Aman) are these two channels joined to each other. This morphological pattern was formed due to the great width of the lower Volga valley bottom: up to 40 km.

Being separate channels, the main Volga River and Akhtuba are connected by the net of small (30–50 m wide) flood plain branches and distributaries, mostly meandering. The water feeds these branches and numerous flood plain lakes during high floods. Due to flood control by the reservoir system the Volga-Akhtuba flood plain is now flooded only quite rarely and the network of flood plain water bodies has degraded.

STRUCTURE OF THE ALLUVIAL RELIEF IN THE LOWER VOLGA CHANNEL

Analysis of functions of spectral density for channel bottom elevations and of histograms of the length of alluvial features (Sidorchuk, 1996), combined with observations of side-looking sonar images of the channel bottom, shows the complicated structure of the bottom relief in the Volga River channel. The complex of bottom forms is hierarchical and consists of four levels: 1: megaripples of mean wavelength 5 m; 2: first order dunes (40 m); 3: 2nd order dunes (140 m); and 4: 3rd order dunes (580 m). With the alternating and braided first order (3100 m) and second order (5900 m) bars, as well as the islands described above, and meanders (13 000 m), the hierarchical structure of the lower Volga River alluvial relief consists of seven levels. This complicated structure was investigated during conditions of stable low water discharge (7 600 $m^3 s^{-1}$) within single channel segments of the river.

Megaripples

Mean length L_R of megaripples is 2–5 m, and their height is <0.1 m. Megaripples are three dimensional bottom forms, easily recognized on the bathymetric profiles and side-looking sonar images.

Dunes

Dunes are most common in the Volga River channel with sandy alluvium. They are marked on the spectrum of channel bottom elevations with a well-defined local maximum.

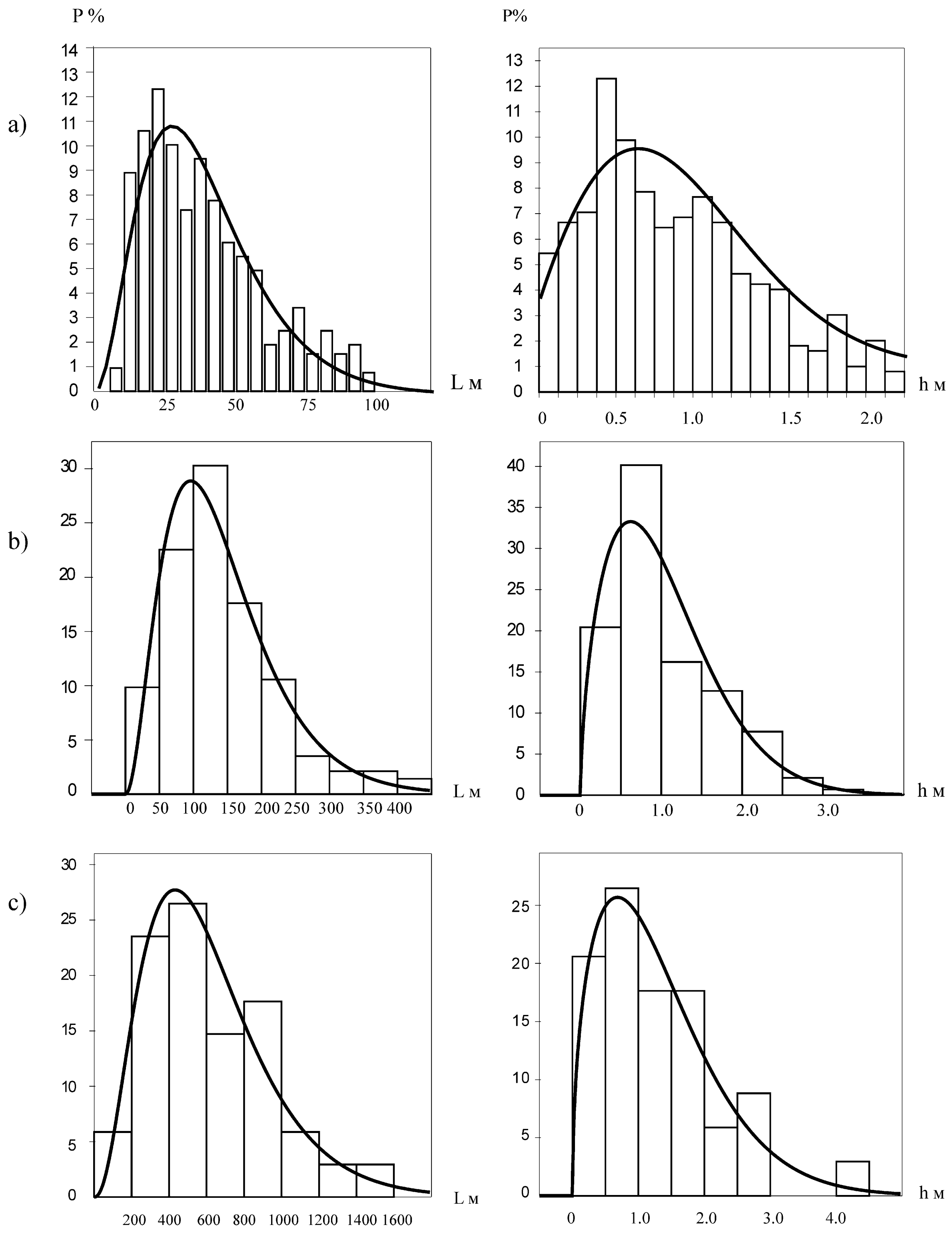

Fig. 3 Histograms and probability density functions for dune length (a), and height (b). For details see the text.

First order dunes have a mean length of 45 m and height 0.8 m. Their distribution fits well to a two-parameter gamma-distribution (Fig. 3(a)):

$$\mathrm{d}p_L = \frac{\eta^{\mu}}{\Gamma(\mu)} L_1^{\mu-1} \exp\left(-\eta L_1\right) \mathrm{d}L_1 \tag{1}$$

where Γ is the gamma function. Parameters $\mu = 3.51$ and $\eta = 0.089$ are correlated with the first order dunes mean length and standard deviation: $L_1 = \mu/\eta$; $\sigma = \sqrt{\mu/\eta^2}$.

The Weibull distribution fits the height variability of the first-order dunes well (Fig. 3(b)).

$$\mathrm{d}p_h = \alpha\lambda h_1^{\alpha-1} \exp\left(-\lambda\, h_1^{\alpha}\right) \mathrm{d}h_1 \tag{2}$$

The parameters of the Weibull distribution can also be estimated using the mean value and standard deviation:

$$h_{1m} = \lambda^{-1/\alpha}\Gamma\left(\frac{1+\alpha}{\alpha}\right);\ \ \sigma_h = \lambda^{-1/\alpha}\sqrt{\frac{2}{\alpha}\Gamma\left(\frac{2}{\alpha}\right) - \frac{1}{\alpha^2}\left[\Gamma\left(\frac{1}{\alpha}\right)\right]^2} \tag{3}$$

For the first-order dunes of the lower Volga River during low water periods, $\alpha = 1.89$, $\lambda = 1.11$.

About 30% of the first-order dunes at the channel bottom were nearly isometric in both longitudinal and cross section. First-order dune asymmetry is described by a normal distribution with the mean equal to 1. The steepness of the downward first-order dunes slope is well described by a gamma distribution with $\mu = 1.95$ and $\eta = 37.8$. That corresponds to a mean steepness of 0.052 and standard deviation 0.037.

First-order dunes are well defined on the side-looking sonar images and are marked two-dimensional bottom features at the low water conditions. Their tops form straight parallel lines across the channel, and their typical sizes can be measured using only one longitudinal bathymetric profile.

Second-order dunes, with a mean length 140 m and mean height 1.0 m, are also common features in the lower Volga River. Their morphology is described with the same distribution curves (Fig. 3), as for first-order dunes. The second-order dune gamma-distribution for length has parameters $\mu = 3.09$ and $\eta = 0.0217$. Second-order dunes profile asymmetry is well approximated by the normal distribution. The Weibull distribution for height has parameters $\alpha = 1.60$ and $\lambda = 0.87$. Mean steepness of downward slope is 0.0234 with standard deviation 0.027, gamma distribution with $\mu = 2.05$ and $\eta = 244.5$ fits well to steepness data. The relatively low steepness of second-order dunes the downward slope makes them practically invisible on the side-looking sonar images, because steeper first-order dunes completely predominate in the image.

Dunes of the third order with mean length 580 m and mean height 1.2 m are less frequent features in the lower Volga River. Nevertheless, there are enough empirical data to obtain statistically reliable distribution curves of their geometry (Fig. 3). Gamma-distribution for third-order dunes length has parameters $\mu = 3.41$ and $\eta = 0.0058$. The Weibull distribution for height has parameters $\alpha = 1.49$ and $\lambda = 0.69$. The mean steepness of the downward slope is 0.0067 with a standard deviation 0.0048; a gamma distribution with $\mu = 2.13$ and $\eta = 318.5$ fits well to the steepness data. Third-order dunes are mainly three-dimensional bottom forms and during low water periods some of them can appear above the water surface. In that case they look like small bars and locally define the configuration of the water flow.

Bars

Alternating bars and braid bars form the internal structure of the channel morphology. These alluvial features have no vegetation or are only partly vegetation covered, and are submerged during the average flood. Alternating bars and braids cause additional sinuosity in the low water flow. There are two orders of bars. Bars of the first order have mean length 3100 m with standard deviation 830 m. A gamma-distribution with $\mu = 14.46$ and $\eta = 0.0046$ can be used for their length description. The height of first-order bars ranges from 2–3 to 11–12 m.

Second-order bars have a mean length of 5 900 m with standard deviation 1 410 m, their height ranges from 4–5 to 12–15 m. A gamma-distribution with $\mu = 20.5$ and $\eta = 0.0035$ can be used to describe their length. Their movement along the islands causes the alteration of resistance to flow in the main channel and the anabranch, which appears in the quasi-periodic decrease and increase of the discharge in the main channel.

RESULTS AND CONCLUSION

The channel of the lower Volga River was formed in a broad valley bottom where the confining factors of the fluvial processes were weak. The bed load and bottom sediments of significant thickness are mainly fine sand, easily reworked by the river flow. Therefore self-organising processes of the fluvial morphology evolution are well developed here, and complicated hierarchical structure characterizes the channel relief.

The highest level of this hierarchy is the two-parallel-channel pattern of the main Volga River channel and Akhtuba, with an anastomosed net of small flood plain distributaries. The two channels flow parallel to each other for a distance about 520 km, and only twice are connected within short segments near Akhtubinsk and Tsagan-Aman.

The Akhtuba and small distributaries mostly have a meandering pattern. The main Volga River channel only meanders close to the delta head. The major part of the channel is sinuous, and shaped like a ∞ (infinity symbol), with the main branch wider and deeper, and the anabranch narrower and shallower, divided by a large island. The sinuosity of the main channel is formed by the combination of the main branches, so if the main branch is right at the upper part of the ∞, it is left at the lower part of the symbol, and *vice versa*. The sinuosity of the main channel is complicated: during the low water period the water flow forms secondary curves due to the existence of alternating bars of the second-order, smaller curves due to the influence of first-order bars and even the smallest curves due to local shallows of associated with third-order dunes.

The bed forms of the lower Volga River channel are organized into a four level hierarchy: megaripples and dunes of three orders. They are partly two-dimensional, and partly three-dimensional features. Their statistical characteristics are similar to those of the bed forms in other rivers and large flumes: the length is described with a gamma distribution and the height with a Weibull distribution. The rather low asymmetry of the bed forms in plan or profile in general is not typical for low water conditions, but can be characteristic for the largest rivers of the lower Volga type.

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