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Effects of width channel increase in the formation and evolution of sandbars (riffles)

Abstract: The paper presents the morphology and the long-term regime of riffles formed in the local widening of river channels: the Ob, the Northern Dvina, and the Ganges. Navigation maps for the last 120 years, detailed channel plans for the last 60 years as well as satellite images from 1977 and further were used to study the long-term regime of riffles. Five types of riffles are distinguished in the widening of river channels. Each type of riffles has a specific regime and a characteristic period of long-term reformations, with both the regime and the period being controlled by local surroundings of riffles. The presented study of the long-term regime of riffles and its relationship with local morphological conditions could be useful to optimize dredging works and, as a consequence, help to preserve optimal conditions of waterways.

Keywords: channel processes, morphodynamic type of channel, morphology and dynamic of riffles and sand bars, types of riffles, river navigation, Ob River, Northern Dvina River, Ganges River.

1. Introduction

The formation, displacement, and main deformations takes place during the period of maximum discharges of water and sediments, which means that these processes result from the movement of the carrying load (Makkaveev, 1955). The long-term regime of riffles depends on their formation conditions, the morphodynamic type of channel, and water discharges in a given year. This regime corresponds to the migration of riffles and their side bars, the growth or partial wash-out of side bars, the migration of riffle troughs within the saddle area, the separation of side bars, the formation of middle shoals and their attachment to side bars (Chalov, 2011). All this is combined with

changes in riffle bottom marks caused by their wash-out (deepening) or in-wash (accumulation of sediments). When formed under the same conditions, riffles have similar dynamic characteristics, deformation mode and time scale of rearrangement, thus enabling the riffles to be divided into types. The long-term mode of deformation of riffles features the cyclic pattern in many cases (Mikhailova, 2015). Riffles formed in the local widening of river channels have a complex morphology and cause the greatest constraints for navigation. Types of riffles are distinguished according to both the shape of the ridge (Zemlyanovsky, 1988), and the regime of long-term deformations.

2. Methods

The research on the formation conditions and the long-term regime of riffles gives the opportunity to predict riffle deformations, maximum depths at riffle ridges, and positions of fairways. The study contributes to the optimization of dredging works, hence the reduction of dredg-

ing costs. The Ob, the Northern Dvina, and the Ganges rivers were selected for the study, because they have weekly stable channels. The study involves analyses of navigation maps of the Northern Dvina River for the last 120 years, navigation maps of the Ob River for the last 44

years, detailed channel plans for the Northern Dvina since 1956, detailed channel plans for the Ob since 2000, detailed channel plans for the Ganges since 2015, as well as satellite images of all rivers since 1977. The analyses include:

- comparison of the navigation maps, detailed channel plans and satellite images;
- determination of displacement rates for riffles under different water levels and water discharges;

- analyses of seasonal and long-term deformations of riffles;
- analysis of distribution of surface and bottom flow rates;
- study of long-term evolution of riffles covering a period of one or a few cycles (discovery of long-term reformation cycles);
- analysis of river bank erosion.

3. Results

Riffles that have a complicated regime and cause serious difficulties in navigation are formed at channel expansion sites. The stream spreading resulted in a significant reduction in the stream transportation capacity, which is the main factor controlling the formation of riffles. The stream separation into branches (Fig. 1A), curvature of a channel (Fig. 1B), confluence of branches and channel bottlenecks (Fig. 1C), secondary bifurcations, large tributaries and confluence of rivers (Fig. 1D) are additional factors of the riffle formation. As a result, shallow riffles are formed with large side bars and

middle shoals, the surface of which is exposed during low-water seasons. The backwater area of these riffles is well developed. The direction of the high-water stream does not correspond to the direction of the low-water stream when bends appear in the channels. The direction of the stream, both at riffles and at riverbed depressions during a high-water season is subparallel to river banks. The direction of the stream at riffles during a low-water season depends on the riffle morphology and on the local pattern of the river channel.

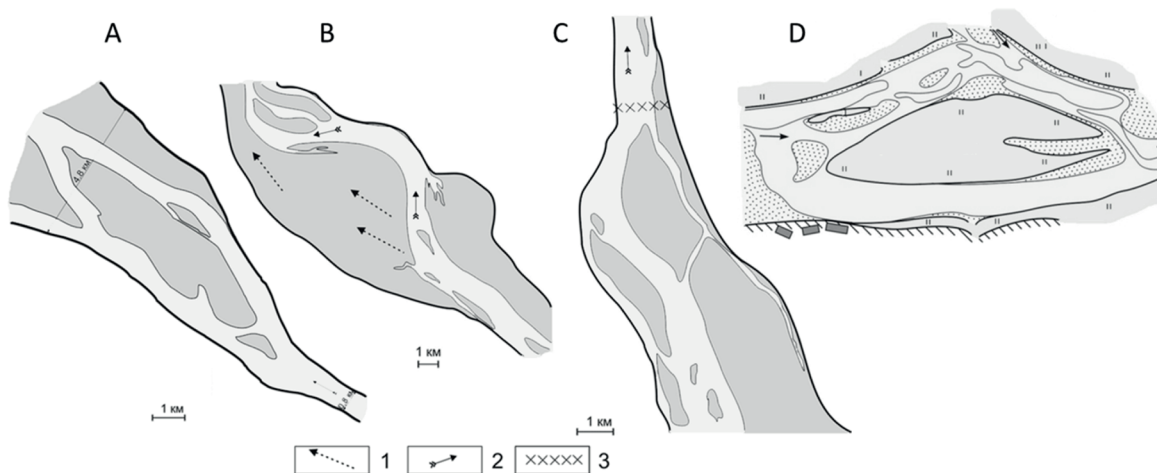


Figure 1. Sites of local channel widening with different conditions of riffles formation. Riffles formation: A – when stream divides into branches; B – when high-water stream does not correspond to low-water stream; C – before narrowing; D – when tributaries enter the main river.

The following section describes the conditions under which seemingly similar riffles develop, however, these are different types of riffles distinguished by their morphology, dynamics, and long-term regime. They all contribute to the curvature of the stream dynamic axis during the low-water period. Considering

the morphology of riffles in channel expansions, those are skewed bars with one, rarely two ridges protruding above the water surface as middle shoals in some years.

If the bifurcation in the channel exists, riffles are formed when the stream divides into branches (Fig. 2A), at the confluence of

branches (Fig 2B), within a branch (if local bifurcation or local channel occurs). If bends are formed in channel expansions, the most complicated riffles are formed near the bend apex (Fig. 2C). Examples of long-term deformations are riffles of the Northern Dvina River.

In the case of a stable stream position along the main bank, riffles with one or two ridges and large side bars are formed when the stream divides into branches. The upper ridge is located near the front side of an island, and the lower one – in the bifurcation branch.

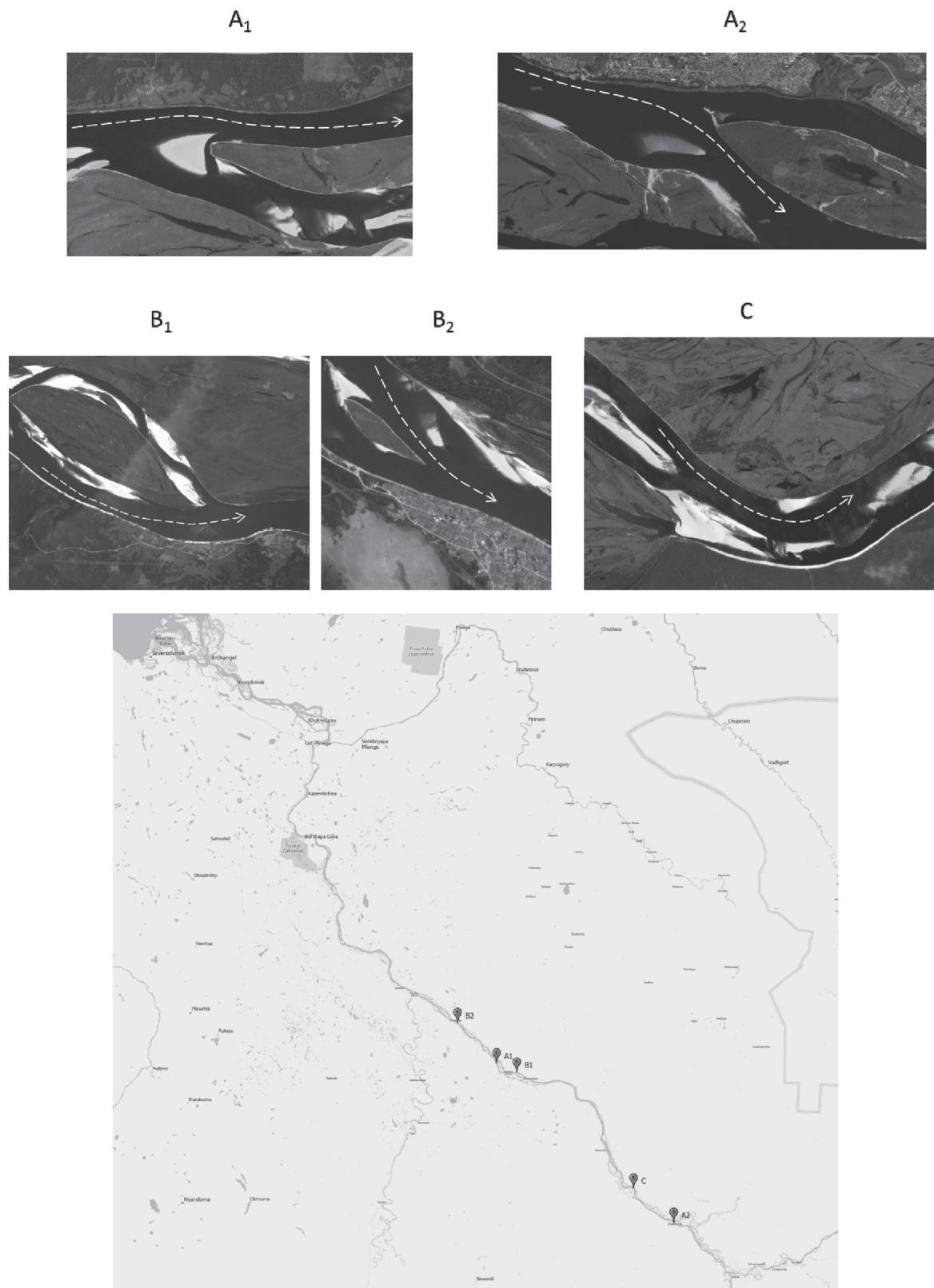


Figure 2. Types of riffles in local channel widening: A – where the stream divides into branches; B – at the confluence of branches; C – in local widening of a meandering channel

The long-term regime of these riffles is characterised by the growth of the upper side bar, the subsequent separation of its part, and the formation of the middle shoal. After some time, the upper shoal attaches to the lower side bar (Fig. 3). These reformations are accompanied by the riffle trough migration, shallowing and washing-out of a riffle, as well as uneven displacement rates of riffle ridges and side bars in the long-term perspective. The range of changes in the displacement rates of riffle side bars is multiplied up to ten times when the long-term changes in the water discharge of a river overlap with the regime of these riffles. As a result, the displacement rates for riffles of this type vary from 5 to 50 m/year (the Northern Dvina, the Vychegda). The rates reach up to 70 m/year at sites with a less stable channel (the Ob in the upper reaches), but the period of long-term reformations is shorter in this case. The average period of reformation cycles is 30–50 years.

The other type of riffles is distinguished for high dynamics in the long-term perspective. These are riffles formed in the place where the stream divides into branches, in the case when the stream passes from one bank to another. As a rule, these riffles appear as two ridges (Mikhailova, 2015). The displacement rates for these ridges are uneven, with rates varying in relation to the stage of riffle development if a long-term cycle is considered. The upper ridge usually moves downstream (with rates of 30–50 m per year) until it enters the zone where the stream leaves the main bank, at which time the displacement rate increases 2–3.5 times (up to 100–170 m/year). At the same time, the new ridge appears upstream (Fig. 4). Therefore, each time the riffle consists of two ridges, each of which moves at different rates. The middle shoal may appear in some years. The complete long-term reformation cycle described covers 30–50 years.

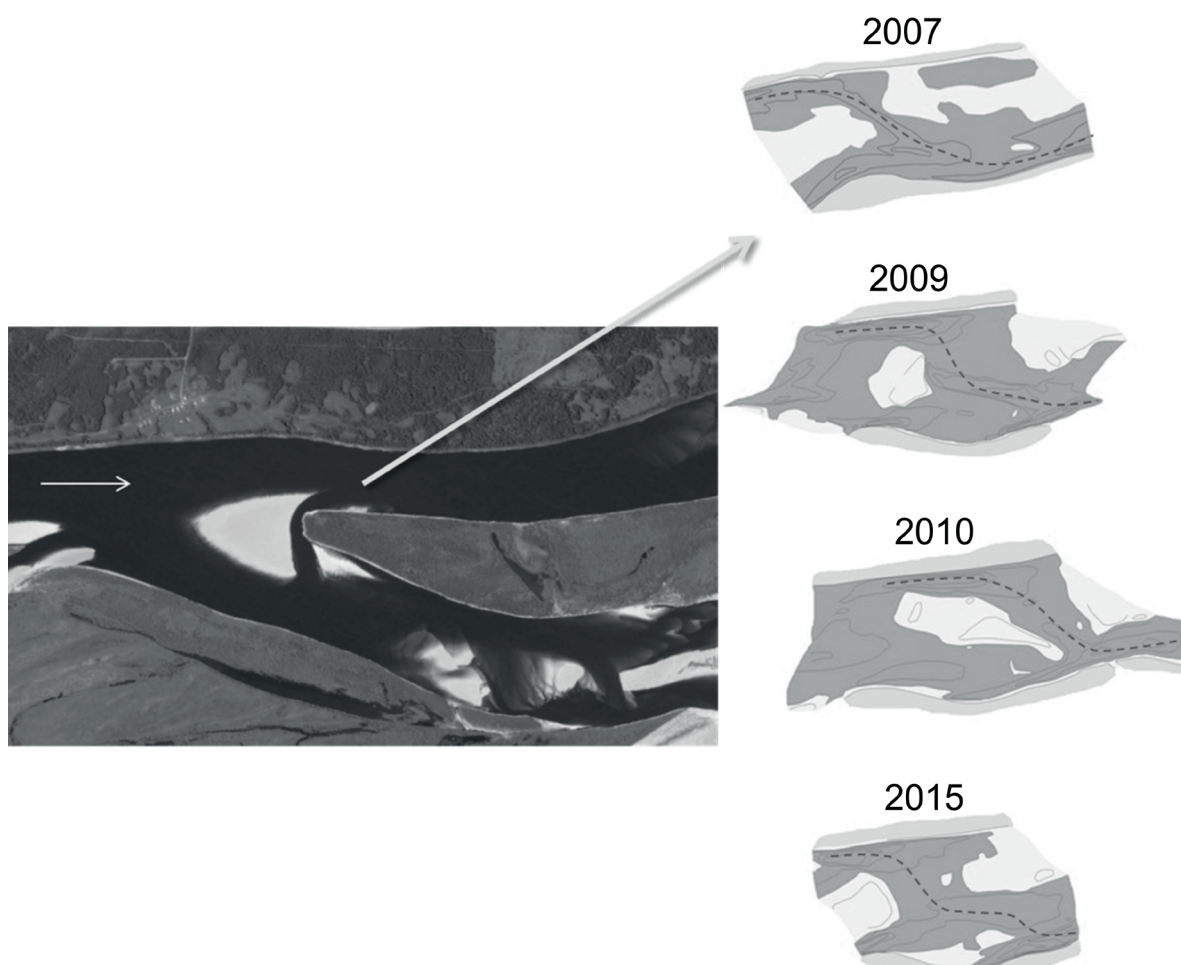


Figure 3. Riffles formed where the stream divides into branches, in the case of a stable stream position along the main bank (the Northern Dvina River)

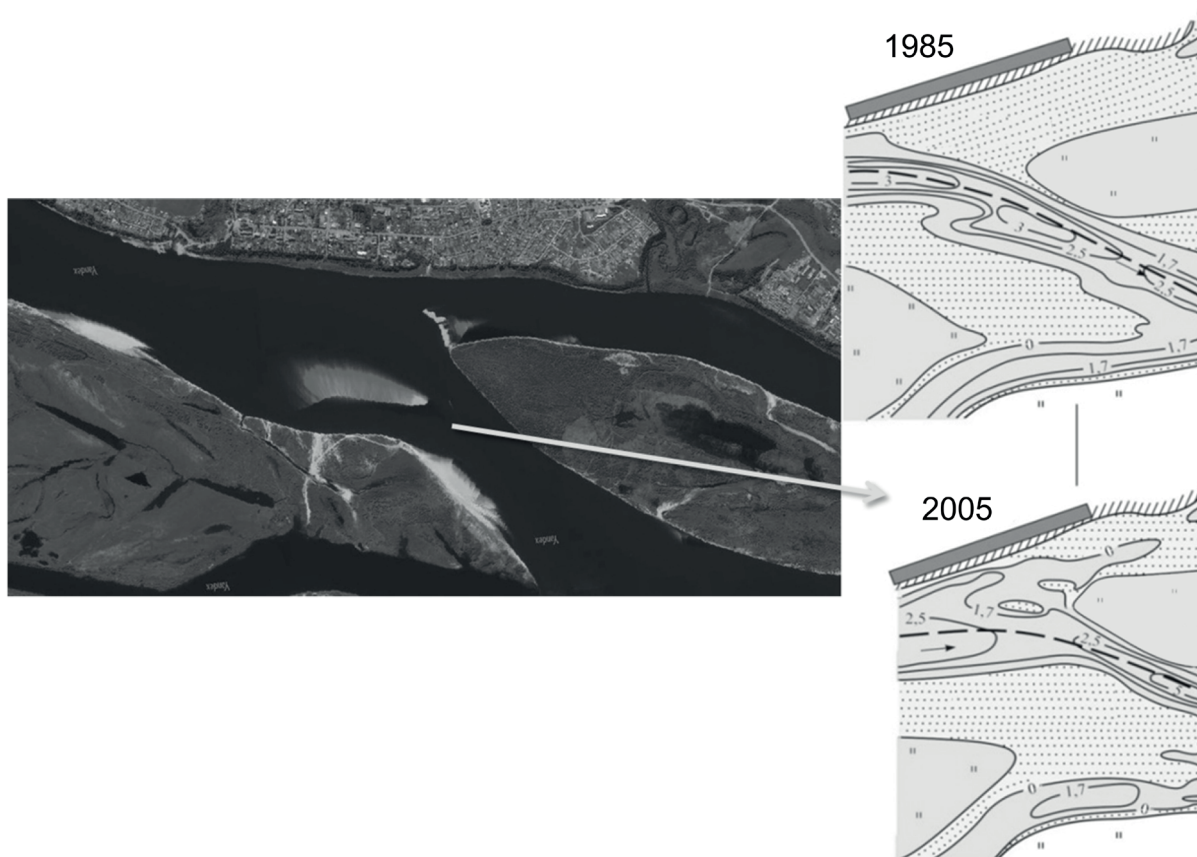


Figure 4. Riffles formed where stream divides into branches (the Northern Dvina River)

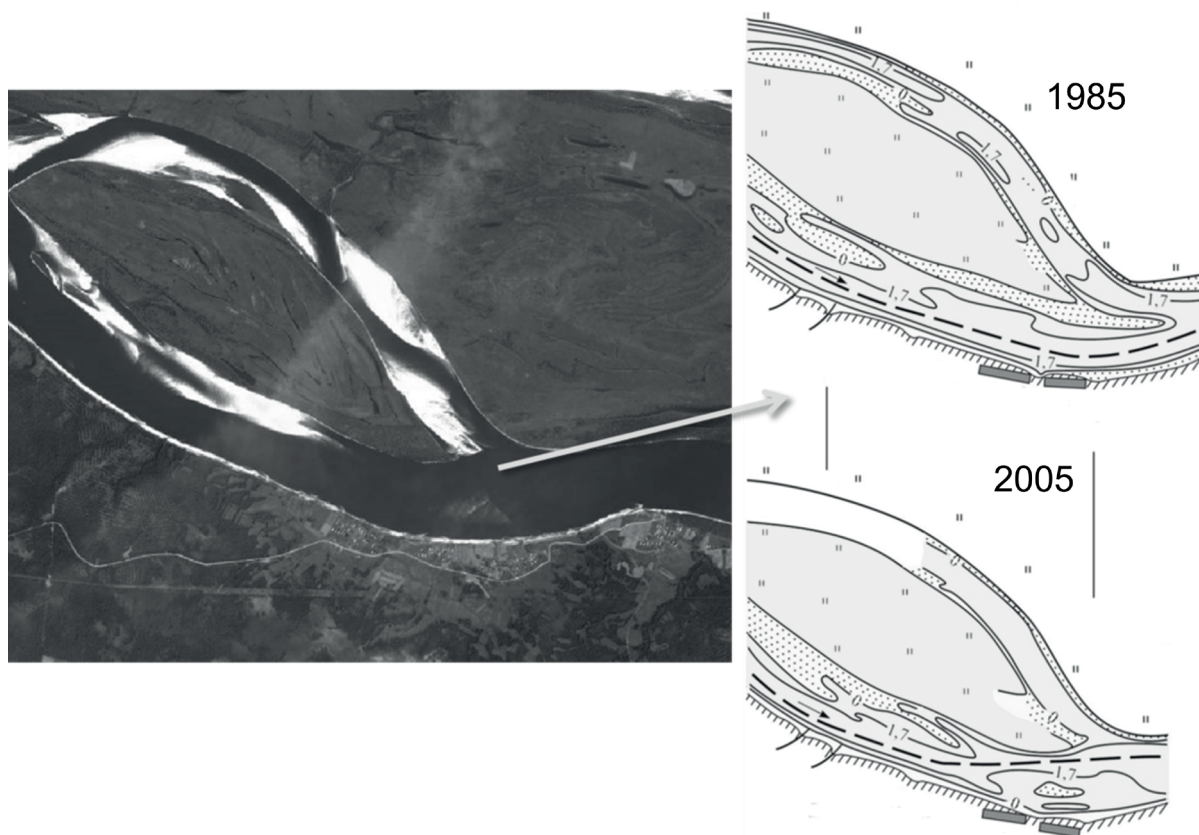


Figure 5. Riffle at the confluence of branches (the stream remains along the main bank) (the Northern Dvina River)

Riffles that formed when branches merge and the stream passes along the main bank have one or two ridges. The upper ridge is formed when the upstream ridge approaches the riffle. The lower ridge is a spit riffle with a well-developed upstream side bar, but without a downstream side bar. The middle shoal is formed during some years as a result of partial spit separation, but the shoal is washed out with time. Therefore, the long-term regime of this type of riffles includes: I – elongation of a spit resulting in riffle displacement downstream at a rate of 30–40 m/year; ii – development of a middle shoal resulting from the migration of the dynamic axis of the stream in the long-term

perspective (Fig. 5). The long-term reformation lasts for 20–25 years.

Riffles with two well-developed side bars are formed at the confluence of branches when the stream passes from one bank to another. The long-term reformation cycle of these riffles involves partial separation of an upstream side bar, formation of a middle shoal, and its subsequent attachment to a downstream side bar (Fig. 6). The cycle lasts 35–40 years, but only 25 years at sites with a less stable channel. The riffle displacement results from the elongation of a downstream side bar. The displacement rates are below 15–30 m/year irrespective of the channel stability.

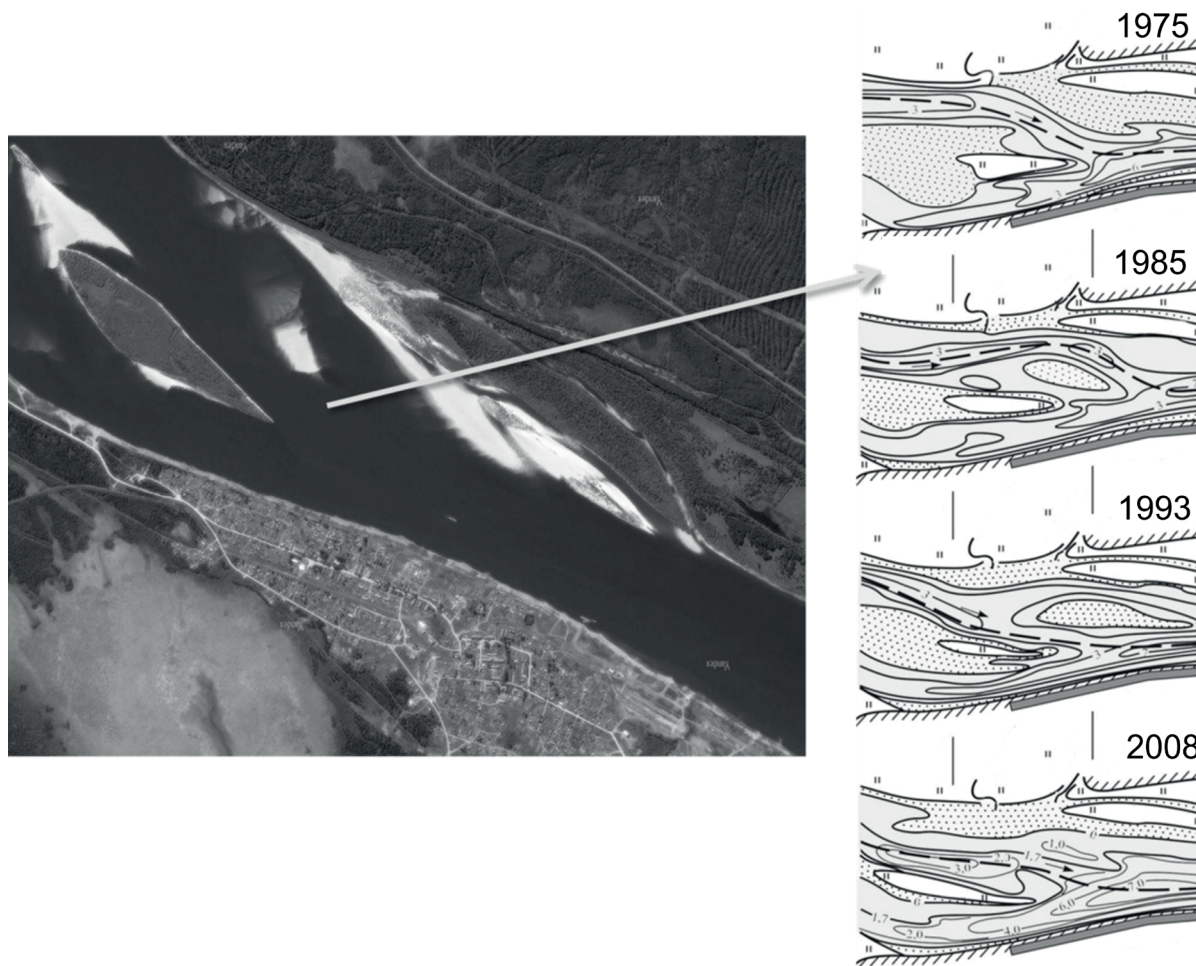


Figure 6. Riffle at the confluence of branches (when the stream passes from one bank to another) (the Northern Dvina River)

Riffles formed near the bend apexes are characterised by the presence of several dynamic stream axes. These axes seem to result from a fan-like spread of a high-water stream in the conditions of rapid increase in the channel width (by 2-3 times). During the low-water period, the stream passes within the riffle trough formed during the high-water period. Therefore, the dynamic axis of the stream curves towards round side bars.

Riffles of this type also exhibit the greatest migration of the dynamic stream axis in the long-term perspective, as well as the formation

of middle shoals and their subsequent wash-out (Fig. 7). The riffles move due to displacements of spits, side bars and middle shoals at an average rate of 40 m/year. The long-term reformation cycle for these riffles lasts for 30–40 years (starting from the growth of side bars and the formation of middle shoals till wash-out of the last ones), but the cycle is longer at the sites with a more stable channel (up to 50–60 years). On the contrary, the displacement rates caused by the growth of spits, side bars and middle shoals decrease (from 40 m/year to 15 m/year) with increasing channel stability.

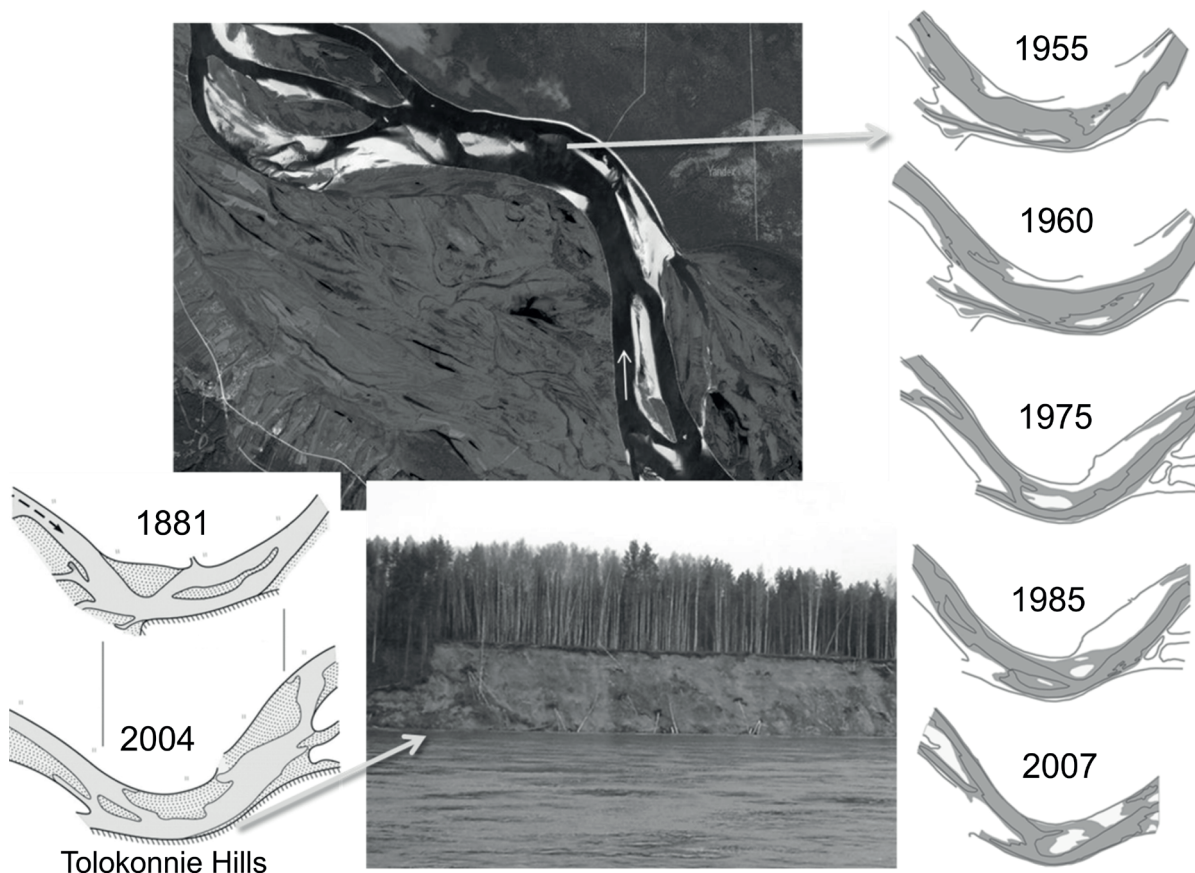


Figure 7. Riffle in local widening of a meandering channel (Northern Dvina River)

If there is a significant supply of sandy sediments along a given river stretch, long riffle sites are often formed downstream the source of the sediment. These sites consist of several riffles of different types separated from each other by short depressions. For example, erosion of a

30 m high terrace in the Northern Dvina River floodplain (the Tolokonnie Hills) contributed to the formation of downstream riffle sites with a total length of more than 30 km (Fig. 8). The concave bank of this bend is being washed out at a rate of 15-20 m/year.

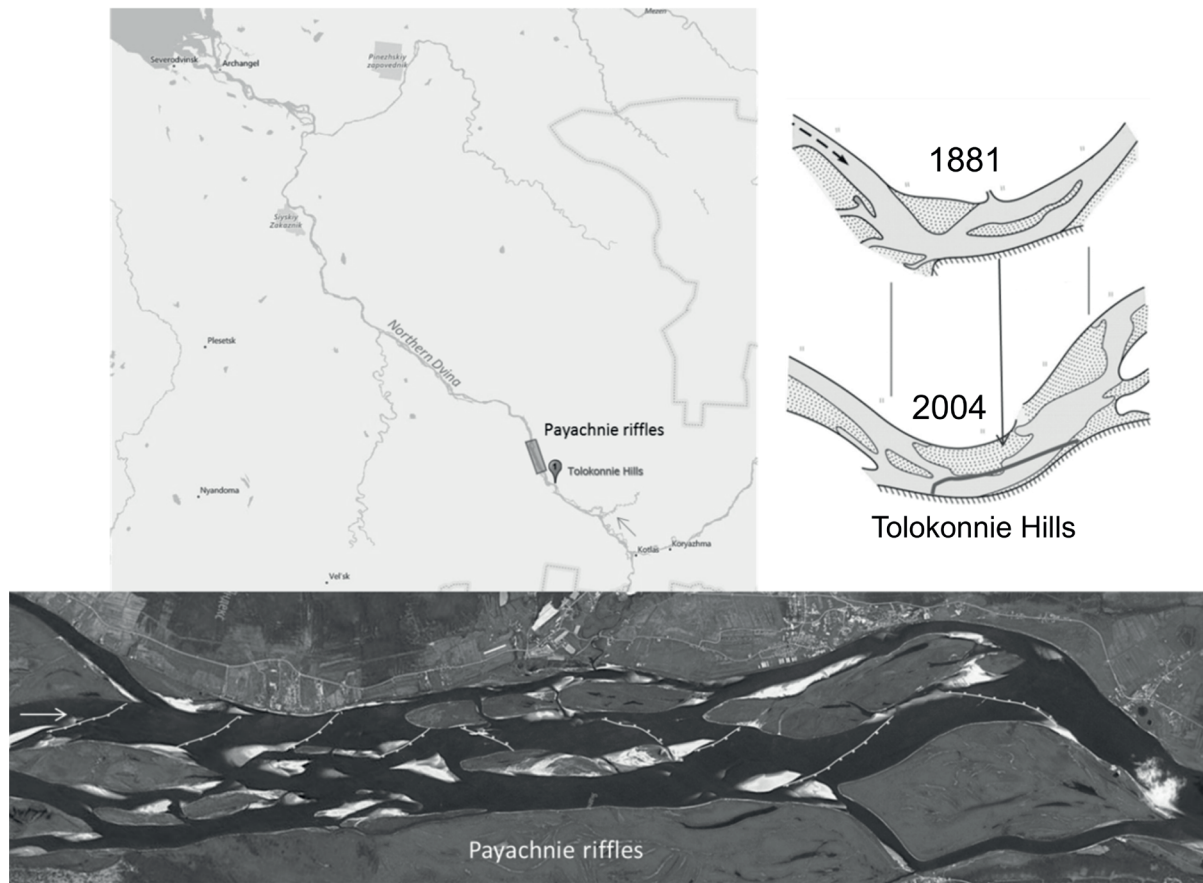


Figure 8. A – washout of the Tolokonnaya Hill escarpment (the Northern Dvina River); B – riffles formed downstream the escarpment

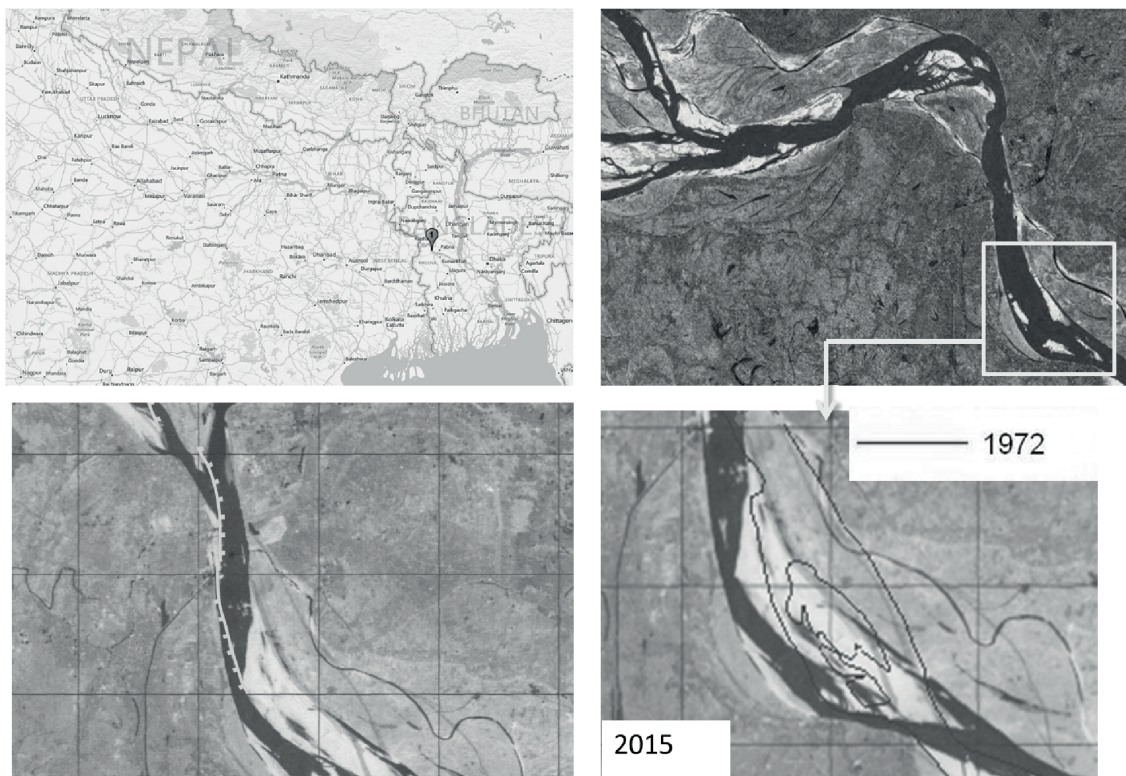


Figure 9. Increased erosion of the right bank of the Ganges River due to the impact of riffles on the low-water stream.

Riffles can affect bank erosion at rivers with an unstable channel. For example, the channel of the Ganges River is composed of easily eroded loess sediments. During the high-water season, bifurcation branches form there, water discharge changes in these branches, riffles develop and regroup. Bank erosion rates approach 160 m/year. Riffles are arranged dia-

gonally to the stream axis, and they cross the channel from one bank to another. Riffles influence the stream during the low-water season, when the stream passes within the riffle trough. As a result, riffles contribute to wash-out of the eroded bank by guiding the stream towards it (Fig. 9).

4. An example of practical application of long-term riffle reformation analyses

One of the most important issues to be solved at rivers is the navigation maintenance. The detailed analysis of channel's behaviour at a given river site is necessary when selecting dredging localities and dredging volumes. For example, both the detailed analysis of long-term channel reformations and the distribution analyses of surface and bottom flow

rates were performed for the site creating navigation constraints on the Ob River (Fig. 10). Based on the conducted analyses, it was recommended to move the fairway from the upstream location to the downstream one, where the midstream flow is controlled during the high-water event.

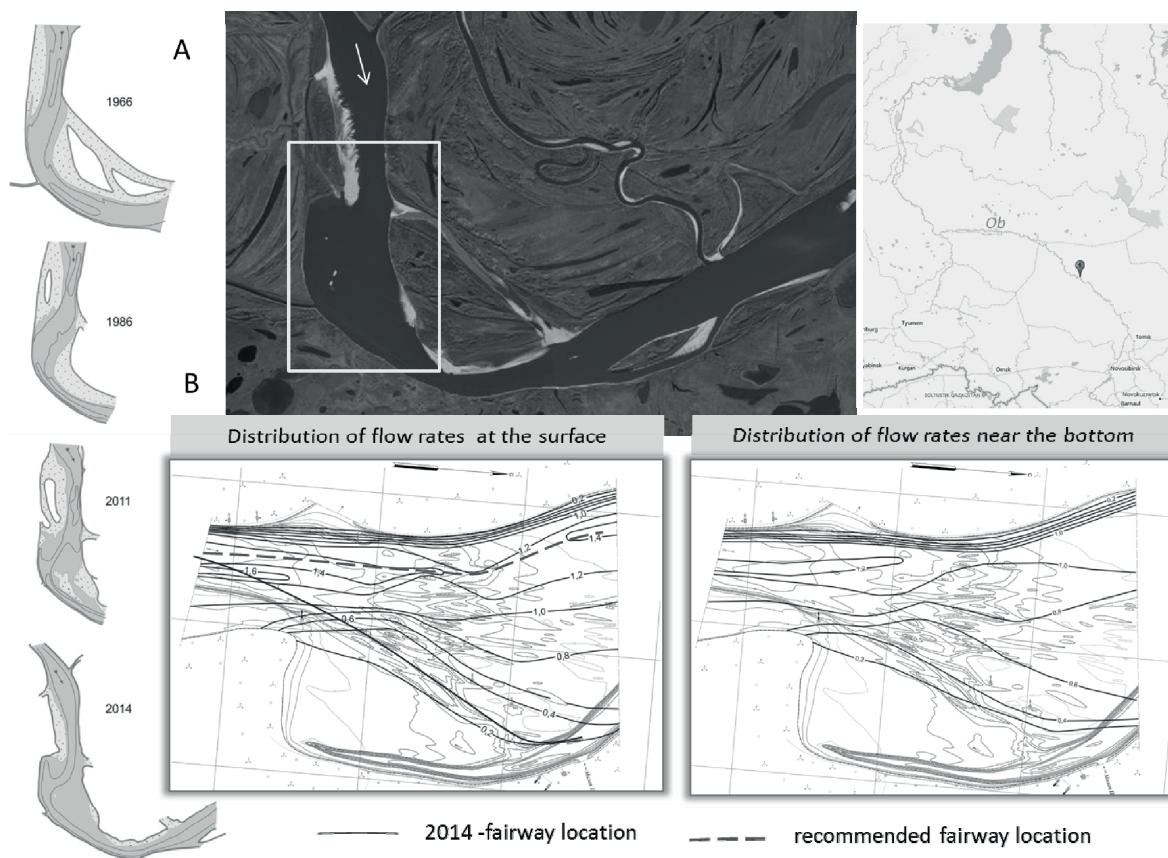


Figure 10. A – long-term reformations at the Ob River site; B – distribution of surface and bottom flow rates, and recommendations for the fairway relocation.

5. Conclusions

On the basis of the detailed study of the selected sections of the Ob, the Dvina and the Ganges, the following conclusions have been drawn:

1. Riffles in the local channel widening are the most difficult to navigate;
2. There are several types of riffles that differ in the morphology, dynamics, and regularity of long-term evolution in the local channel widening;
3. There are basic patterns and regularities (duration of cycles) in the long-term evolution of different types of riffles. Migration of sand material through rolling, separation of side sandbars, formation of middle sandbars are characteristics of nearly all types of riffles;
4. Division of a high-water stream, mismatch between high-water stream and low-water stream, the development of side sandbars, the long-term formation of middle sandbars, which leads to bending of the dynamic stream axis, and are characteristic for the majority of riffles in the local channel widening;
5. The comprehensive study of the long-term regime of riffles in the local channel widening helps to optimize dredging and re-routing of navigational routes in a timely manner when necessary due to deteriorating shipping conditions.

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