Deformations of curvilinear river channels subject to thermoerosion

E I Debol'skaya1,2, I I Gritsuk1,3,4 and O Ya Maslikova1

1 Water Problems Institute, Russian Academy of Sciences, Moscow, Russia
2 Moscow State University of Civil Engineering, Moscow, Russia
3 RUDN University, Moscow, 117198 Russia
4 Moscow Automobile and Road Construction State Technical University, Moscow, 125319 Russia

e_debolskaya@yahoo.com

Abstract. This study focuses on the deformation of curvilinear segments of the channels of rivers flowing in the permafrost, under a combined effect of water flow and thermal erosion. A mathematical model presented in this article consists of three blocks: thermal, hydrodynamic, and deformation. The model has been tested against data of laboratory experiments.

1. Introduction

Systematic studies of permafrost began in the first half of the 19th century. The study of the features of water flows in permafrost began only in the 70s of the 20th century due to the discovery of oil and gas deposits here in the 60s. The need to take into account these features when laying pipelines on the seacoasts and in the floodplains of the Arctic rivers predetermined the development of studies on the effects of sea waves and river flows on the transformation of coasts composed of permafrost. The projects of transfer or use of the northern rivers in populated areas played their role in the development of these studies not only in the Soviet Union, but also in the United States and Canada. Nevertheless, the analysis of the literature shows that work on coastal deformations of the Arctic seas began to develop most intensively only in the last decade, and research on the transformation of river channels is still very little. One of the first literature reviews of these studies was the work [1], published in 1979, in which the author emphasizes the important role of Soviet researchers in the cryolithozone (permafrost) and, in particular, the processes of thermal abrasion of coastal river slopes. Many terms used in this field of knowledge have since been tracing paper for Russian names. For example, the term "niche thawing", introduced by R.V. Abramov in 1957, is widely used by foreign authors and is now known as thermo-erosional niching. The enduring relevance of cryolithozone research is evidenced by the holding of international congresses (Permafrost Conference). Unfortunately, after the appearance of work [2] at the first congress in 1963, there were few similar studies [3-5]. The results of research on the degradation of the Arctic sea shores, which have been successfully carried out recently with the use of high-tech methods, can be used to some extent for estimating river deformations. An example is the work [6]. A large contribution to the study of channel-forming processes in the cryolithozone is made by works [7–9].

Climatic fluctuations according to numerous observations at the present stage are expressed in a marked increase in air temperatures in the Arctic regions. The influence of warming has been devoted
in recent decades to a huge amount of research, reflected in scientific articles, conference proceedings, and analytical reviews. Interest in these studies is due to the increasing practical importance of the Arctic zone, rich in mineral deposits, primarily hydrocarbons, and not least environmental problems. One of the problems associated with the degradation of permafrost is landscape changes, including coastal deformations. Delta areas are particularly affected. However, the interest of researchers is mainly limited to the seacoast and deltas; it is difficult to find work on the study of river coastal deformations. Their results are reflected primarily in the works of Russian and French scientists [10–12], who confirmed that a number of key parameters have changed, since the middle of the last century. The water temperature in the Lena River, for example, during the flood period increased by 2 °C compared with the figures for 1950, which led to a change in the processes affecting the development of thermal and mechanical erosion of the banks. The increase in the rate of thermal erosion since the beginning of the 80s fully correlated with the rise in temperature of the water stream due to warming. In some areas, the coastal retreat rate reaches 20–40 m per year, and leachable rocks are carried along with the flow and create difficulties in navigation. The development of information and computational technologies contributes to the construction of mathematical models, with the help of which it is possible not only the forecasting of channel processes in permafrost conditions, but also an in-depth study of numerous interrelations that must be taken into account when studying them.

Earlier studies of deformations of river channels subject to thermal erosion, based on the results of laboratory and numerical experiments [13–16], have been carried out for rectilinear channels. The results obtained in them can be used in calculations and forecasts for not very long segments, as it is known that all natural watercourses, because of a complex combination of the involved forces, which are mostly determined by land surface topography, have a curvilinear form, i.e., are meandering. This article studies the deformation processes in curvilinear channel segments.

2. Materials and methods
To validate and verify the mathematical model, three series of experiments were carried out in a flume with different forms of channel curvature, each series containing two experiments – with and without ice inclusion in the bank slope. The objective of the experiments was to explore the role of ice inclusions in the deformation of channels subject to a combined mechanical and thermal effect of water flow at different types of channel meandering. In the first series of experiments, the deformations were examined in a channel with a form of a half-period sinusoid with a widening. The mean depth of the water flow was 7 cm, and the flow discharge was 3.5 l/s. An ice plate 1.5 cm in thickness and 15 cm in width was placed in the widest part of the channel. In the second series, the channel had a form of a half-sinusoid with a narrowing, and an ice plate of the same size as in the first series was placed in the narrowest part of the channel. The third series of the experiments was carried out in a channel with a form of a full period of sinusoid, and two ice plates each 3 cm in thickness were placed in the narrowest and widest sections. The former two series lasted for 15 min each, and the third series lasted for 30 min. In all cases, the ice plates had melted completely during the experiment.

The hydrodynamic block of the two-dimensional mathematical model used a complete system of transient hydrodynamic equations. The form of the channel showed a sinusoidal dependence of channel width on the length. The deformation module of the model was used to calculate the changes of bed elevation by channel deformation equation (the mass conservation law for water-born sediments). On the solid boundaries and on the right boundary (receiving reservoir), zero fluxes were specified; while, on the left (entry) boundary, the fluxes were taken to vary depending on water inflow regime. In the calculations corresponding to the data of laboratory experiment, zero sediment flux was specified, because clear water was always supplied to the laboratory installation. Engelund dependence was used to complete the system. In this version of the model, a parameter of soil ice content was introduced in channel deformation equations to incorporate the frozen soil and ice plates in a single model. In the thermal module, the soil temperature was calculated with the use of a homogeneous heat-conduction equation, and Stefan equation was used to calculate the motion of
water–soil interface. Water temperature remains constant throughout the laboratory experiment. In the mathematical model, at the initial moment, the soil temperature is assumed negative all over the soil volume while water temperature is assumed positive.

Numerical experiments were carried out in accordance with the laboratory scenarios given above. Figures 1 and 2, which give photos of laboratory experiments and the surface of drained channel, constructed by the data of numerical experiments, show the agreement between these results, which is also confirmed by estimates of maximal deformations.

Figure 1 shows a scenario with a channel in the form of a complete sinusoid with two ice plates (3 cm × 15 cm), introduced in a bank slope in its narrowest and widest places.

![Figure 1. The situation after 30 min of the laboratory and model time. The ice has melted almost completely. Water has been partially drained.](image-url)

The comparison of quantitative characteristics of deformations at different channel forms can be made with the use of a channel form factor $k_f = \frac{L S_0}{a S}$. Here $L$ is the length of the bank line in the channel segment; $a$ is the shortest distance between the sections that bound it; $S_0$ is the actual planar area of water flow; $S$ is the total area of the entire segment under consideration $S=ab$; $b$ is channel width with neither widening nor narrowing taken into account, i.e., measured in the sections that bound the channel segment. Note that if an even number $n$ of segments with identical forms with alternating narrower and wider places can be identified in a segment, as is the case with a full sinusoid or several sinusoids, then the form factor will consist of a single relationship $k_f = L/a$, because the total area of an actual segment $S_0$, limited by the bank line will be equal to the area of the rectangle $S$. The assumption that the total deformations in such segments are independent on the order of occurrence of convex and concave forms was confirmed by the numerical experiments for 2, 4, and 6 half-sinusoids. If two successive convex–concave forms (two half-sinusoids or two triangles) are considered as a single form (a complete sinusoid), it can be easily shown that the sum of $k_f$ such forms is equal to the form factor of an entire sinusoid or two triangles. Does this imply that the total deformations of two successive segments with a convex and concave forms of the same areas (with a half-sinusoid or a triangle), calculated separately, will be equal to the deformation of a segment with a single convex–concave form (full sinusoid)? Numerical experiments have shown that such equality will hold only when the bank slopes contain no ice inclusions.

3. Results
Figure 2 gives the curves of total deformations as functions of channel factor for scenarios with no ice inclusions; with a single ice plate located in the middle of a bent bank slope; with two ice plates, located symmetrically; and with a continuous ice plate along the entire bent bank (a hypothetical case).
Figure 2a corresponds to single forms; and figure 2b, to repeating forms. The full lines correspond to deformations calculated on a bent bank and on the bed; and dashed lines, to those calculated for the entire segment, including the opposite straight bank.

**Figure 2.** Dependence of total deformations on channel form at different number of ice inclusions.

**Figure 3.** Dependence of total deformations on water temperature.

Numerical experiments were carried out to analyse the effect of a stronger thermal impact of the water flow. As known from observations, water heating by 2 degrees, for example, in the Lena River, causes an increase in deformations by 20%. The cases of a continuous ice plate, located in a straight bank segment and in segments with the form of a convex and concave half-sinusoid and a full sinusoid were simulated. The results given in figure 3 as changes in the total deformations accompanying water temperature rise demonstrate the agreement between the obtained results and field data.

**4. Discussion**

Single channel forms (figure 2) show a tendency toward an increase in erosion with increasing concentration of ice inclusions, especially, as compared with the scenario without ice. In the case of repeating forms, the deformation patterns differ for the entire channel segment where erosion is predominant and for a bent bank with adjacent bed, where deformations are mostly positive. In such
case, an increase in the concentration of ice inclusions results in an increase in erosion in the entire segment and a decrease in accumulation at a bent bank. The character of the dependence of changes in the deformation on bank form is the same for all curves. An increase in the form factor causes an intensification of positive deformations at a bent bank segment, though with a greater erosion all over the segment. Therefore, an intensification of transverse transport can be seen.

The intensification of deformations at an increase in the thermal impact (figure 3) shows a considerable effect of channel form. Thus, at a straight channel, an increase in water temperature does not cause changes in the character of deformations after some temperature regime has established. This is most likely due to the fact that the melting out of ice is taking place uniformly all over the bank and does not lead to changes in its configuration, velocity field, and, therefore, sediment transport, as opposed to the case with a complex channel form.

5. Conclusion
The proposed model of deformation processes in curvilinear segments of river channels, which are subject to a combined dynamic and thermal impact of water flow, adequately reflect the examined process, as can be seen from the comparison of the data of numerical and laboratory experiments; therefore, this model can be used to forecast the development of different situations, depending on the external and morphometric parameters.

An integral parameter of channel form is proposed to characterize the difference between possible deformations. This parameter can be used for the comparison of the results of analysis of numerical experiments.

The intensification of deformations at an increase in thermal impact shows a considerable effect of channel form.

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