Gradient fill fairway plotting method for mapping inland waterways

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Abstract. This article proposes a method for plotting fairways using gradient fill of digital terrain models of the bottom relief. The purpose of the method is to improve the accuracy of fairway plotting, ensuring the safety of both manned and unmanned navigation. Non-regulated fairways are usually plotted by eye. When done this way, the accuracy of the fairway placement directly depends on the cartographer’s capability and initial data. Gradient fill allows the operator to instantly and accurately assess bottom relief, without having to analyse text. Gradient fill is used to fill a digital terrain model of the bottom relief built based on an irregular depth grid densified via the biquadratic spline interpolation.

1. Introduction
For the development of cartography departments and services of the Water Authority of the Inland Waterways (hereinafter ‘WAIW’), it is necessary to improve the production process of electronic navigational charts (hereinafter ‘ENC’). The introduction of computer technologies into the development and production of the charts, namely expert systems, neural networks, pattern recognition systems, and other kinds of artificial intelligence along with digital modelling of the bottom relief, will make it possible to automate the laborious processes of creating various types of charts, as well as introduce objectivity in establishing the positions of the characteristic points and lines of the relief [2].

At present, part of the inland waterway mapping process, including fairway plotting (fairway is the section of the waterway best suited for the movement of ships), is carried out manually. It does not require any additional time or skills if the fairway is regulated since, in this case, its location and boundaries are determined by the available navigational aids (hereinafter ‘NA’). However, in the case where there are no waterway marks on the banks or NA enclosing the fairway, the quality of plotting such navigation information depends directly on the cartographer’s capability and initial data. In such a case, the fairway is plotted based on the analysis of measured depths, considering that the number of manoeuvres performed by the shipmaster or unmanned vessel must be minimised.

The fairways shown on the electronic charts are used to plot the routes of not only manned but also unmanned vessels. It is this navigation information that is crucial for the safety of navigation since inland waterway navigation conditions include specific dimensions and tortuosity of the fairway, numerous
navigational hazards both within and near its edges [3], and limited visibility. The curvilinear sections of the fairway must be determined with more accuracy, since the position of the vessel on the axis of the fairway depends on the presence of cross-currents, lingering currents, the speed of river flow and wind drift current, meaning that the vessel occupies a larger navigation lane than in the straight sections of the fairway [4].

2. Materials and methods
To facilitate cartography work, namely to easy the placement of fairways when mapping inland waterways (hereinafter ‘IW’), non-regulated NA, speed up the correction of automatically created isobaths, and provide additional visual control of the quality of survey work, the authors of the article propose using digital terrain models of the bottom relief (hereinafter ‘DTMBR’). At present, DTMBR are used as an independent solution for a variety of tasks, from basic data analysis to complex modelling [5]. DTMBR are able to most fully convey information about changes in objects and the investigated area over time and solve certain applied tasks that cannot be solved with two-dimensional data [6]. Modern geoinformation software features perspective panoramic three-dimensional modelling and plan oblique relief mapping [7]. Various scientists propose using bathymetric models for navigation purposes, as well as the basis for compiling three-dimensional navigational charts [3]. The use of DTMBR for IW mapping was first proposed by the authors of this article.

The data obtained from surveying with a single beam echo sounder [8] is insufficient for DTMBR because the maximum permissible inter-haul distance in reservoirs can be up to 500 meters [9]. In this regard, it becomes necessary to build on the relief of the bottom of the waterway using mathematical methods. Grid densification is not needed when surveying with a multi-beam echo sounder [10].

Mathematical interpolation is the optimal method for survey grid densification. The analysis of the accuracy of DTMBR built using various interpolation methods is described in the papers authored by European, Australian and American scientists [Chaplot et al., 2006 [11]; Li et al., 2008 [12]; Erdogan, 2009 [13]; Guo et al., 2010 [14]; Amante et al., 2016, 2018 [10], [15]; Parente et al., 2019 [8]; Wu et al., 2019 [16]; Carnevale et al., 2020 [17]. The results of the analysis showed that spline (function defined piecewise by polynomials) interpolation allows creating DTMBR with the lowest errors for various terrain conditions [8, 10, 15, 16, 17, 18]. Therefore, the authors of the article use the biquadratic spline interpolation method for grid densification. Interpolation is performed on a triangulation model built using the Delaunay method [19].

The constructed grid is filled with a gradient fill. With the gradient, we can see the values not only at key vertices (measured or interpolated depths) but also between them. The process of filling with a gradient fill serves as an analogue to bilinear interpolation since in mathematical representation a gradient fill is a vector that indicates changes in a certain value with its direction, with the value changing from one point in space to another.

For a three-dimensional Cartesian space with the gradient of the scalar function \( \varphi = \varphi(x, y, z) \) of coordinates \( x, y, z \) with components \( \frac{\partial \varphi}{\partial x}, \frac{\partial \varphi}{\partial y}, \frac{\partial \varphi}{\partial z} \), there is a vector function

\[
\text{grad } \varphi = \nabla \varphi = \frac{\partial \varphi}{\partial x} e_x + \frac{\partial \varphi}{\partial y} e_y + \frac{\partial \varphi}{\partial z} e_z,
\]

where \( \frac{\partial \varphi}{\partial x} e_x, \frac{\partial \varphi}{\partial y} e_y, \frac{\partial \varphi}{\partial z} e_z \) are the partial derivatives of the function. Thus,

\[
\text{grad } \varphi = \frac{\partial \varphi}{\partial x} e_x + \frac{\partial \varphi}{\partial y} e_y + \frac{\partial \varphi}{\partial z} e_z = \frac{f(x_1, y_1)}{\Delta} k_1 + \frac{f(x_2, y_2)}{\Delta} k_2 + \frac{f(x_3, y_3)}{\Delta} k_3 + \frac{f(x_4, y_4)}{\Delta} k_4,
\]
where

$$\Delta = (x_1 - x_0)(y_1 - y_0),$$

$$k_1 = (x_1 - x)(y_1 - y),$$

$$k_2 = (x - x_0)(y_1 - y),$$

$$k_3 = (x_1 - x)(y - y_0),$$

$$k_4 = (x - x_0)(y - y_0).$$

The fairways are plotted along the darkest area of the gradient fill, but in such a way as to ensure the minimum steering angles and curvature coefficients along the entire length.

Figure 1 shows a fragment of a bathymetric model of the Neva River with automatically created isobaths and fairway plotted along the gradient fill.

Figure 1. A fragment of the bathymetric model of the Neva River with automatically created isobaths (depicted in yellow) and fairway plotted along the gradient fill (depicted in red).

3. Results and Discussion

To analyse the accuracy of fairway placement, the authors of the article used the source materials and ENC of the Tavda River. A fragment of the Tavda River ENC created by a cartographer without the use of DTMBR is shown in Figure 2.

Based on the initial measurements obtained in the section of the Tavda River using a single beam echo sounder, the authors of the article built the Delaunay triangulation. The depth grid was then densified using the biquadratic spline interpolation method. Figure 3 shows a Tavda River ENC with automatically placed 1.2m safe isobath and a fairway plotted along the gradient fill of DTMBR.

Figure 4 shows a Tavda River ENC with fairways manually plotted by a cartographer without using DTMBR (depicted in red) and with fairways plotted along the gradient fill of DTMBR (depicted in dark red). In the lower left corner, the fairway plotted by eye is placed outside the guaranteed depths.
Figure 2. A fragment of the Tavda River ENC created by a cartographer without the use of DTMBR (in S-57 format). Safe isobath 1.2m and fairway plotted by eye.

Figure 3. A fragment of the Tavda River ENC (in S-57 format). Safe isobath 1.2m placed automatically. Fairway plotted along the gradient fill of DTMBR.
Figure 4. A fragment of Tavda River ENC. The fairway was placed manually without the use of DTMBR (depicted in red) and along the gradient fill of DTMBR (depicted in deep red).

Figure 5 demonstrates an overlay of an ENC created without the use of DTMBR and ENC created with DTMBR. ENC Designer software in Combi Mode was used to display the chart. Significant differences in the placement of isobaths and, as a consequence, in the placement of fairways can be seen in the lower left corner of Figure 5. Figure 5 shows that the 1.2m safe isobath is placed incorrectly without the use of DTMBR.

Figure 5. Differences in the placement of isobaths and fairways on ENC created without DTMBR (depicted in yellow) and ENC created based on mathematically built DTMBR (depicted in red)

On the presented ENC and DTMBR of the Tavda River (Fig. 4 and 5), we can see that the fairway
plotted manually based on thinned depths crosses the area of dangerous depths (safe isobath). Determining the correct placement of the fairway is necessary to ensure the safety of navigation. Therefore, whenever it is possible to presume the existence of unsafe areas (e.g. shallows) along vessel traffic routes based on the DTMBR, it is necessary to perform an additional more detailed survey of the area.

4. Conclusion

One of the methods for automating IW mapping is filling constructed digital terrain models of the bottom relief with a gradient fill, which is particularly necessary to facilitate fairway plotting.

Gradient fill allows the operator to quickly assess bottom relief without having to analyse text. Filling a bathymetric model with a gradient fill allows to instantly place isobaths (if it’s not automatic) and plot fairways in sections that are not regulated with NA.

Comparing fairways plotted without DTMBR and fairways plotted with DTMBR and a gradient fill reveals significant differences in their placement. Incorrect fairway plotting, namely their placement outside the guaranteed depths, can cause accidents, especially for unmanned navigation. Whenever it is suspected that the fairway was placed along a section of the waterway with depths insufficient to ensure safe navigation, it is necessary to perform additional hydrographic survey.

Based on the analysis of the accuracy of fairway plotting using the regular method and the method proposed by the authors, it can be concluded that it is necessary to use DTMBR with a gradient fill for IW mapping since the gradient fill fairway plotting method increases the reliability of the charts.

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