DETERMINING INLAND WATERWAY PARAMETERS WITH
APPLICATION TO THE SAVA RIVER

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Summary

The article provides a definition of inland waterway parameters with the emphasis on the international waterway classes IV, Va and Vb relevant to the Sava River. The parameters have been defined through the comparative analysis based on international classification of inland waterways, the available theoretical assumptions, and available and published physical model researches. The channel parameter problems have not been considered herein.

The philosophy of the applicable UN/ECE classification of 1992 consists in defining the relevant waterway structures and navigable water levels only. The waterway parameters are then determined in compliance therewith for each individual waterway based on the navigable channel morphology, through the morphological, technical and economic analysis. Through such an iterative procedure, a detailed standardization of the Sava River waterway parameters was created for the international classes IV, Va and Vb, serving as a basis for the current analysis of the Sava River navigability for the purpose of gaining informative concept of the scope of water works to be executed and the financial dimension of requested works for short-term and long-term periods.

Key words: inland waterway, the Sava River, waterway class, standardization, river bed morphology

1 Introduction

The primary objective of this article is to conduct an analysis of the Sava River waterway on the basis of the international treaty, the international classification of inland waterways and the theoretical assumptions. The analysis in the first part of the article thus exclusively deals with the waterway parameters for the natural rivers. Since the Republic of Croatia is a signatory of the AGN [1] Agreement, only the international navigable waterway parameters of the IV, Va and Vb classes related to the navigable Sava River have been considered herein. Namely, Croatia declared the Sava River within the AGN Agreement as a waterway of the IV class (minimum international class for the existing waterways). The Danube-Sava multipurpose channel was declared to be the waterway of Vb class. However, in the far future, there is an option of raising of the waterway class to Va or Vb (minimum international class for a new waterway on rivers and channels).
Based on the analysis of the Sava River morphology, below is the estimate of the technical interventions needed to meet with the requirements of the international navigability class of the Sava River, currently IV, and in the future Va and Vb class. The estimate of financial requirements is also made along with the estimated technical interventions.

1.1 Relevant Vessels, Vessel Convoy, Navigable Water Level, Manoeuvres during Navigation and Navigation Speed

Relevant vessels and the respective convoys used in this analysis have been defined within the UN/ECE classification of 1992 [2]. The international waterway of class IV shall provide navigation to self-propelled ship of the following dimensions: length l=80-85m; width b=9.5 m, draught t=2.5 m, bearing capacity 1000-1500[t] as well as to stiff pushing convoys such as lighter of type E1 + push-boat of dim. \( l_{\text{max}} \times b \times t = 85 \times 9.5 \times 2.5 - 2.8 \text{[m]} \), deadweight 1000-1500[t], [1 and 2]. Pushing convoy is relevant. The relevant vessels for the future classes (Va or Vb) are stiff pushing convoys consisting of a lighter type E2 + push-boat, and \( 2 \times E2 + \) push-boat.

For the navigable water level, the following is adopted:

- **VPV** [cm or m a.s.l.]: High navigable water level: water level of 1 to 3% duration
- **V₆₅%** [cm or m a.s.l.]: Water level of 65% duration at which all waterway parameters shall be fully met,
- **NPV** [cm or m a.s.l.]: Low navigable water level: water level of 95% duration at which the navigable channel need not be completely met, i.e. the navigable channel depth shall be provided with 60% of the full depth.

Navigation with great caution, reduced safety and frequently reduced speed represents a manoeuvre. There are four greatly different types of manoeuvre on the waterway: overtaking, passing by, turning and passing under a bridge. For the inland waterway analysis, the relevant manoeuvre is passing by on the river or the channel waterway.

In respect of the navigation speed on natural rivers, the following is adopted:

- \( v_s = 12 \text{ km/h} \) for self-propelled ship, speed in still waters or a relative vessel speed;
- \( v_s = 9 \text{ km/h} \) for pushing convoy, speed in still waters or a relative vessel speed.

1.2 Former Inland Waterway Parameter Research

In order to calculate the detailed plan view parameters of the navigable channel in the river bend, the minimum radius of the waterway shall be selected based on the morphological analysis, and then the corresponding navigable channel width shall be calculated. The quantity of training works shall then be specified, and the minimum radius changed, if needed. The minimisation of development costs is generally achieved by the introduction of one-way navigation at certain points because of the state border and zoning problems. The analysis is therefore very complex and interactive. On the other hand, in the UN/ECE classification [3] of 1960, in the Danube Commission Recommendations [4] of 1975, in the PIANC analyses [5] of 1999 regarding the Vb class, as well as in the existing radius values within the European waterway network there is information concerning approximate minimum radius values, which still may be accepted in the navigation practice. In case of stiff pushing convoys of the international class IV to VII, the
theoretical ratio of the navigation channel width in the bend and its radius is defined by the drift angle $\beta$ for stiff pushing convoys. In theory, experimental parameters have been specified only for the class IV. These parameters may also be applied with certain departures to the class V because of the similarity of the convoys. On the basis of above mentioned procedure, the minimum navigation channel radius on the Sava River have been selected herein and waterway parameters in the bend have been determined per classes. Since the natural rivers consist of bends and counter-bends, i.e. there are no long directions, the parameters in the bend are relevant for the entire river section of uniform morphology.

<table>
<thead>
<tr>
<th>INTERNATIONAL CLASS</th>
<th>natural rivers</th>
<th>canalized rivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN/ECE 1960.</td>
<td>The Sava Initiative</td>
<td>UN/ECE 1960. The Sava Initiative</td>
</tr>
<tr>
<td>IV</td>
<td>350-650</td>
<td>360</td>
</tr>
<tr>
<td>Va</td>
<td>-</td>
<td>360</td>
</tr>
<tr>
<td>Vb</td>
<td>450-750</td>
<td>450</td>
</tr>
</tbody>
</table>

Tab. 1 Minimal radius of the navigable channel in the bend on the Sava River in comparison with local and international waterways according to the UN/ECE classification of 1960

By specifying the above mentioned input parameters, it shall be possible to elaborate the analysis of a minimal navigable channel width on the rivers (in the direction and in the bend), as well as other parameters such as the navigable channel depth.

1.3 Applied Research Methods

Since the waterway parameters have not been specifically defined by the international classification (or standardization), the procedure for the standardization of parameters of the Sava River is hereby proposed on the basis of comparative analysis of the existing recommendations, theoretical assumptions and the available experimental research.

On the basis of standardized waterway parameters and by the analysis of the morphological characteristics of the Sava River, the water works needed to ensure the Sava River to comply with the international waterway standard may be estimated. In addition to the estimate of the necessary water works, the estimate of work costs was also carried out.

2 INLAND WATERWAY PARAMETER ANALYSIS

2.1 Waterway Width in the Direction

The intention is to define the minimum waterway width in the direction for the two-way navigation of the inland waterway of IV, Va and Vb class, which is critical during the low navigable water level. It consists of two parallel navigable tracks: for upstream and downstream navigation of one self-propelled ship or one one-row pushed convoy (Fig. 1). (Evidently, during higher water levels, navigation of two-row pushed convoys, parallel towing convoys and self-propelled ship convoys by a barge tied „under the arm“ shall be possible).
The navigation in the direction on the meandering river is so rare that it does not exist as a rule. The navigation is from the bend into the counter-bend. Nevertheless, the direction navigation has also been presented as it is of fundamental importance for the following analysis of the navigation in the bend. Considering the track width, the navigation in the bend with the radius exceeding 2000 m corresponds to the navigation in the direction. In that case, the drift angle of the vessel or of the stiff convoy in the bend $\beta$ is more or less equal to the wriggle angle of the vessel or of the stiff convoy in the direction $\Delta\beta$, and the tracks are more or less of the same width. During navigation in the direction, it is important that the vessel or the convoy departs, i.e. wriggles in the attempt of keeping the direction. One of the reasons for wriggling is hydrodynamic, i.e. wriggling occurs because of the propeller drifting, the unevenness of the channel and water flow, the unevenness of the vessel and cargo arrangement, and particularly because of the action of the wind pressure force on the superstructure. The second reason for wriggling occurs in the case of asymmetric navigation, passing by or overtaking in the restricted waterway, depending on the layout of the vessels where they become laterally shifted or attracted. Therefore, for safety reasons, it is necessary to define the wriggling angle $\Delta\beta$ (Fig. 1). According to Wiegleb [6], the experimental horizontal wriggling angle of the vessel or of the convoy, $\Delta\beta$ varies from $1.5^\circ$ to $3^\circ$, where:

$\Delta\beta_1=1.5^\circ$  
horizontal wriggling angle of the vessel or of the stiff convoy in the case of upstream navigation,

$\Delta\beta_2=3^\circ$  
horizontal wriggling angle of the vessel or of the stiff convoy in the case of downstream navigation,
Verification of the experimental wriggling angle $\Delta \beta$ has been made on the basis of an experiment [5] conducted in Munich on the physical river model in the direction, in 1:25 scale in the nature. The model corresponds to the natural river section 1300 m long and 157 m wide with the „Lochnestein“ self-propelled ship (95 m x 11.4 m).

Following the example from the experiment [5], for the bank slope 1:3, the self-propelled ship $l_{\max} = 95$ m, the minimum safety distance between the bank and the ship $a=6 - 7$ m and the upstream navigation in the direction, the drift angle $\Delta \beta \approx 3^\circ$ is derived. For the vertical bank with $a= 5$m, $l_{\max}=95$m and downstream navigation, the drift angle $\Delta \beta \approx 3.5^\circ$ is derived. In this way, experimental drift angle during the navigation in the direction was verified as indicated in [6].

The navigable channel widths for the two-way navigation in the direction $B_{F,r}$ have herein been determined analytically, on the basis of the available theoretical and practical methods [6] [7] [8] [9] [10] [11] for all classes of waterways. Accepting the terms as referred to in Fig. 1, it is obtained as follows:

$$B_{F,r} [m] = S_S + B_r + S_S = S_S + (2 \times b + S_B + 4 \times \Delta b/2) + S_S = 3.5 \times b + 2 \times \tan 3^\circ \times l_{\max} = 3.5 \times b + 0.1 \times l_{\max} \quad (1)$$

Where:

- $B_{F,r} [m]$ width of a two-way navigable clearance on the river during overtaking in the downstream navigation in the direction,
- $B_r [m]$ width of two-way navigable channel in the direction on the navigable river,
- $S_S [m]$ horizontal reserve between navigable clearance and river profile,
- $S_B [m]$ horizontal reserve between vessels, i.e. convoys.

In this classification has been adopted $S_S=S_B=0.5 \times b$. The term $\Delta b= \tan \Delta \beta \times l_{\max}$ is used, where $\Delta \beta=3^\circ$ in conformity with the above conducted analysis. Relevant general conditions have been applied as follows: passing by is taken as relevant maneuvre on the rivers.

### 2.2 Waterway Width in the Bend

The following approach has been applied to all natural and canalized rivers of IV – VII class where the pushing technology is dominant. Specific values are provided for the Sava waterway of IV, Va and Vb class. The waterway width in the bend $B_{F, r, c}$ in principle depends on the minimal radius $R_{\min} [m]$ of the waterway bend axis, while in the actual calculation the radius of internal edges $R_i [m]$ of each navigable track are used (Fig. 2).

Navigable tracks in the bend are much wider than the tracks in the direction. Whereas the vessels in the direction only wriggle with the angle of maximum horizontal rotation of $\Delta \beta=\pm 3^\circ$, the vessels in the river bend in the downstream navigation drift with the angle of horizontal rotation of up to $20^\circ$. Drifting is less expressed in the upstream navigation because „the rudder obeys better“ and therefore the upstream track is narrower. The expression for the two-way navigable channel width
in the bend in the case of passing by manoeuvre \( B_{F,r,c} \) (Fig. 2) includes upstream and downstream navigable tracks and reads as follows:

\[
B_{F,r,c} [\text{m}] = S_S + B_r + S_S = S_S + \{B_1 + S_B + B_2\} + S_S = \{B_1\} + \{B_2\} + 1,5 \times b =
\]

\[
\begin{align*}
B_{F,r,c} &= \left( R_{l,1} + b \right)^2 + \left( \frac{l_{min}}{2} + \left( R_{l,1} + \frac{b}{2} \right) \tan \beta_1 \right)^2 - R_{l,1} \ + \left( R_{l,2} + b \right)^2 + \left( \frac{l_{min}}{2} + \left( R_{l,2} + \frac{b}{2} \right) \tan \beta_2 \right)^2 - R_{l,2} \ + 1,5 \cdot b \\
&= \left( R_{l,1} + b \right)^2 + \left( \frac{l_{min}}{2} + \left( R_{l,1} + \frac{b}{2} \right) \tan \beta_1 \right)^2 - R_{l,1} \ + \left( R_{l,2} + b \right)^2 + \left( \frac{l_{min}}{2} + \left( R_{l,2} + \frac{b}{2} \right) \tan \beta_2 \right)^2 - R_{l,2} \ + 1,5 \cdot b 
\end{align*}
\] (2)

Where:

- \( B_{F,r,c} [\text{m}] \) - width of a two-way navigable channel on the natural or trained river in the bend in the case of passing by (Fig. 2)
- \( R_{l,1} [\text{m}] \) and \( R_{l,2} [\text{m}] \) - radius of internal edge (nearer to the curve center) of navigable track \( B_1 \) in upstream navigation and \( B_2 \) in downstream navigation on the natural or trained river in the bend (Fig. 2).
- \( \beta_1 [^\circ] \) and \( \beta_2 [^\circ] \) - horizontal drift angle of the vessel or of the stiff pushing convoy in the bend in upstream and downstream navigation on natural or trained river (Fig. 2).

Other: ditto equation (1).

The procedure of determining the navigable channel width in the bend for any class of waterway by the expression (2) is iterative. The analysis of the Sava River class IV, Va and Vb is presented in Fig. 3. The following general conditions were relevant in determination: minimal radius for the Sava 360 m, the horizontal drift angles \( \beta_1 \) and \( \beta_2 \) for the calculation of the navigable track width \( B_1 \) and \( B_2 \), are interpreted from the expression (2) in upstream and downstream river navigation in the bend depending on the \( R_{l,1} \) and \( R_{l,2} \) radius and on the central angle of the navigable channel bend \( \alpha=30[^\circ] \) as indicated in the Graewe's experimental diagraph [7]. The central angle \( \alpha=30[^\circ] \) was used as for larger central angles, the width of tracks \( B_1 \) and \( B_2 \) remains constant [12].
diagraphs have been made for stiff pushing convoys consisting of one or two lighters E1 tied in a series. Other conditions are the same as referred to in Chapter 2.1.

### Fig. 3 Width of navigable channel in natural and trained rivers. The case of passing by in the curve. R-minimal radius.

#### 2.3 Waterway Depth

The needed depth of the navigable channel T as on channels so on natural rivers is determined by: vessel draught – t, longitudinal vessel trim - Δt, vessel speed sink - Sz, imprecision - γ and absolute reserve - Φ [9]:

\[ T = T_v + \gamma + \Phi = (t + \Delta t + Sz) + \gamma + \Phi = t + C \]  

where:

- \( T_v \) [m]: navigable clearance depth
- \( t \) [m]: vessel draught
- \( \Delta t \) [m]: longitudinal trim of one vessel
- \( Sz \) [m]: speed sink
- \( \gamma \) [m]: imprecision (measurements, excavations or back fill of a river or channel bed cross-section)
- \( \Phi \) [m]: absolute reserve
- \( C \) [m]: underkeel clearance
The navigable channel depth for international depth classes of the Sava waterway, calculated as referred to in (3), are shown in Fig. 4. In this case, the following general conditions were relevant: for the calculation of the navigable channel depth, regional waterways (< of IV class) have to provide the smaller draught than 2.5 [m], the existing international (IV class) minimum 2.5 [m], and the future international Va and Vb minimum 2.8 [m] [2 and 5]. – The dynamics of navigation in the vertical plane essentially depends on the cross-section restriction of the waterway, therefore it is similar with natural and canalized rivers, and different with channels. For the determination of the navigable channel depth in two-way navigation, central navigation in the direction and full speed of the vessel or the convoy are relevant. The depth defined in this way is valid for the entire navigation channel width. Longitudinal trim of one vessel adopted from experience is: \( \Delta t = 0.1 \) [m]. Speed sink values \( S_z \) of IV to Vb class of waterway on channels or rivers are interpreted or estimated from the Kuhn's experimental diagraphs [8]. Since there are no diagraphs for all classes, the most similar existing diagrams were used. Absolute reserve is taken for the class IV: \( \Delta t = 0.3 \) [m] and for the class V: \( \Delta t = 0.4 \) [m]. The reserve due to imprecision is taken as an arbitrary value: \( \gamma = 0.3 \) [m]. The waterway depth for the maximum draught should be provided at \( V_{65\%\text{ AGN}} \) [1]. On smaller natural rivers, which achieve their navigable channel depth for maximum draught at high water levels only, it is recommended to reduce, at low navigable water level (which corresponds to the water level of 95% duration) the navigable channel depth by up to 60% of the depth calculated for the maximum draught. It is being adopted that the canalized rivers, which are constructed almost as artificial watercourses intended for navigation, shall guarantee safe navigation with maximum draught at low navigable water level corresponding to the water level of 95% duration.

**Fig. 4** Depth of navigable channel in natural and trained rivers.

### 2.4 Detailed parameters for waterway classification on the Sava river
The parameters which were analyzed in previous chapters and other parameters were used as a base for enactment of decisions [14], [15] and [16]. These decisions have defined legal scope for classification of Sava river waterway by the International Sava River Basin Commission.

3 The Sava River Navigability Analysis

The Croatian section of the Sava from Račinovci to Sisak was especially analysed. As per the AGN Agreement, the mentioned section of the Sava under the designation E-80-12 was listed in the European waterway of IV class. However, in its present state the following sections do not comply with the declared class: 203+300 (Račinovci)–305+700 (Sl. Šamac) IV. class, 305+700 (Sl. Šamac)–330+200 (Oprisavci) III. class, 330+200 (Oprisavci)–363+200 (Sl. Brod-grad) IV. class, 363+200 (Sl. Brod-grad)–594+000 (Sisak) III. class. The section 583+000 (Sisak)–651+000 (Rugvica) has not been declared an international waterway and has II. class [13] (Chainage in Sava kilometre marks). Based on the conducted analysis of the morphological characteristics of the Sava there are 8 critical waterway sections (Fig. 5) from Račinovci to Sisak [17], needing waterworks in order to comply with the IV class criteria. In the scope of work [19] has analyzed remain part of Sava waterway from Belgrade to Račinovci.

![Fig. 5 Critical sections of the Sava waterway in Croatia requiring considerable water works in order to comply with the class IV criteria from Sisak to Brčko and class Va criteria from Brčko to Račinovci (Chainage of the Sava navigable canal) [17]](image)

In the decision [20] section from Sisak to Brčko is declared as IV class and from Brčko to Belgrade as Va class. Decision to apply IV class from Brčko to Sisak is mainly because of morphological reasons as well as from state and ecological reasons. "No cut off meanders" principle was adopted.
The financial resources needed in order to achieve IV class for the Sava waterway (from Belgrade to Sisak) have been estimated based on the consideration as referred to in [19], as follows in the Tab. 2. It was not predicted to use the cut-offs in the meanders, instead, one way navigation in the bends and points for waiting are assumed.

<table>
<thead>
<tr>
<th></th>
<th>Total for SCC Class IV [Euro]</th>
<th>Total for SCC Class Va [Euro]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dredging and training works</td>
<td>34,929,200</td>
<td>39,108,600</td>
</tr>
<tr>
<td>Environmental costs</td>
<td>1,005,000</td>
<td>1,340,000</td>
</tr>
<tr>
<td>Bridge replacements</td>
<td>8,880,000</td>
<td>8,880,000</td>
</tr>
<tr>
<td>River bend improvements (total)</td>
<td>11,360,000</td>
<td>11,360,000</td>
</tr>
<tr>
<td>Markings and sunken vessels</td>
<td>1,835,000</td>
<td>1,835,000</td>
</tr>
<tr>
<td>RIS</td>
<td>5,790,000</td>
<td>5,790,000</td>
</tr>
<tr>
<td>Net cost</td>
<td>63,799,200</td>
<td>68,313,600</td>
</tr>
<tr>
<td>Including contingencies (+10%)</td>
<td>70,179,120</td>
<td>75,144,960</td>
</tr>
<tr>
<td>TOTAL project costs (+15%)</td>
<td>80,705,988</td>
<td>86,416,704</td>
</tr>
</tbody>
</table>

Tab. 2 Estimated financial resources for achieving Class IV and Va for the Sava waterway from Belgrade to Sisak [16]

In order to achieve IV class for the Sava waterway upstream from Rugvica the unit price per kilometre should be almost 9 times higher than downstream from Rugvica [19].

4 Instead of Conclusion

The parameters IV, Va and Vb of the international waterway classes have been developed for the purpose of the Sava waterway classification and training. Those parameters have been obtained by comparative analysis of the inland waterway parameters, made on the basis of international classifications, available theoretical presumptions, and available experimental tests. Based on the so set standards, the analysis of morphological characteristics of the Sava from Račinovci to Sisak was performed, in order to reach conclusions on the scope of the required waterworks for the purpose of achieving the declared international class IV and Va of the Sava waterway.

The IV class waterway with the navigable channel of 72×3.6[m] and the minimal radius of 360[m] may be executed through river training works at 31% of its length. The navigable clearance does not comply at 29% of the length, and the minimum radius 2% of the length. It is thus being recommended that the direct water works’ measures be implemented in order to achieve complete correction of the navigable channels and that meander cut-offs should be avoided at too low radius due to state and ecological reasons. The navigation in those places shall be one way for the standard push convoy, while for smaller towed convoys and smaller self-propelled ships it may be two-way. Va waterway was also analyzed for the purpose of comparison. The navigable channel being 89×4.0[m] (including somewhat reduced towing) does not comply at 40%, while the minimum radius of 360[m] does not comply at 2% of length.

Given to decision [20] where IV class from Sisak to Brčko and Va class from Brčko to Belgrade were provided, class Vb which is considered in this paper is hardly expected in foreseeable future.

The financial load of the required works for the purpose of achieving the conditions for the international class IV of the Sava River navigability from Račinci to Sisak has been estimated to about 80,000,000 Euro. The realization is to be sought in interstate agreements in about 5 to 10 years time.
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