Navigational Characteristics of Lower Sava – Determining Draught and Carrying Capacity of Ships

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This paper presents the procedure for calculation of possible values of draught of ships or barges in pushed convoy while navigating through certain sections of Lower Sava which have characteristic shapes and dimensions. The goals of the paper is to, based on known calculation procedures, determine the value of possible draughts of ships or pushed convoys through this section with restrictions in navigating conditions, or to determine periods of the year when ships or pushed convoys can achieve best results during exploitation.

Key words: ship; barge; navigation, water levels; limited depths; limited draughts

1. INTRODUCTION

The Danube, besides that it connects Serbia and Croatia, at the same time connects the whole region not only to other countries on the Danube, but to the countries of the Middle East as well. This waterway carries significant part of international trade of the countries in the region. With the navigational connection Rhine-Mine-Danube ships have open access to waterways of Western Europe (France, Belgium, and The Nederland) as well as access to waterways of northern Germany and central Europe. At the same time Lower Sava presents a connection Croatia and Bosnia and Herzegovina with the Danube until the building of channel Šamac-Vukovar is finished (The idea of building this mentioned channel exists well over 40 years and so far it has remained only as an idea).

River Sava is the second longest tributary of the Danube and it is 945 km long and it is created when Sava Dolinka and Sava Bohinjka merge near Radovljice. To Ljubljana it is a mountain river and from Ljubljana to Zagreb the slope of the river is redu-

ces significantly as it enters Pannonian Plain.

Between the mouth of river Kupa all the way to its mouth Sava river's slope has gradient of 42 mm/km, which makes it become a low land river which meanders a lot. Due to such low gradient of the slope Sava river is not capable of transporting alluvium brought by its tributaries which then settles near mouths of those tributaries and creates large number of shallows and sand bars. These shallows and sand bars are mostly present downstream from mouths of rivers Bosna and Drina and between Kupa and Una, which during low navigation levels makes navigation difficult or completely impossible.

Figure 1 - The schematic depiction of lower Sava [1]

River Sava is navigable for ships from the mouth of River Kupa on the river kilometre (rkm) 583 to its mouth into the Danube. Regarding the navigation and referring to specific characteristics of waterway river Sava can be divided into three characteristic parts:

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- Upper Sava, from the mouth of river Kupa (rkm 583) to Bosanska Gradiška (rkm 459);
- Middle Sava, from Bosanska Gradiška (rkm 459) to Sremska Mitrovica (rkm 136), which due to its specific navigation conditions is divided into sub-sectors Bosanska Gradiška (rkm 459) – Slavonski Brod (rkm 364); Slavonski Brod (rkm 364) – Brčko (rkm 220) and Brčko (rkm 220) – Sremska Mitrovica (rkm 136);
- Lower Sava (Figure 1) from Sremska Mitrovica (rkm 136) to Belgrade (rkm 0), according to classification by The International Sava River Basin Commission [2] Lower Sava consists from following parts from the navigation view point:
 - Mouth of the river Sava rkm 0,0 – Kamičak rkm 86,0 (class IV)
 - Kamičak rkm 86,0 – Mišar rkm 102,0 (class III)
 - Mišar rkm 102,0 – Šabac rkm 107,0 (class IV)
 - Šabac rkm 107,0 – Kalovica rkm 111,8 (class III)
 - Kalovica rkm 111,8 – Sremska Mitrovica rkm 136 (class IV)

Hydrological and morphological factors have crucial role on navigating conditions. Most favorable conditions for navigation are during stagnating average water levels while most unfavorable conditions are during low and high water levels.

Research of exploitation characteristics of ships on Lower Sava sector is based on the results of previous analysis that the authors have done for certain sectors of the Danube [3], [4], [5], [6], and [7].

In order to complete the picture on navigational characteristics of river Sava the authors have used, apart from their own data, research and data from [8] and [9].

Figure 2 - Šabac sector, rkm 114 to rkm 84 [1]

Since ships and pushed convoys are designed to navigate both the Danube and Sava it is necessary for them to have technical and exploitation characteristics dictated by those two navigation areas. Starting from this fact this paper will analyze navigational characteristics of river Sava on the sector from the mouth of

2. BASIC NAVIGATIONAL CHARACTERISTICS OF LOWER SAVA

Lower Sava from Sremska Mitrovica to Belgrade has all the characteristics of lowland river – low speed of river flow, large number of river bends, large widths of river bed, large number of river islands and backwaters, as well as higher depths. Authoritative hydrological stations, according to which navigation on Lower Sava is managed, are in Sremska Mitrovica, Šabac and Belgrade. Hydrological station in Sremska Mitrovica, besides its significance for navigation on Lower Sava, is of special interest for navigation on Sector of Rača (from rkm 176 to rkm 168). Water level on hydrological station Šabac is very important for navigation on Šabac sector (from rkm 110 to rkm 78). Water level on Šabac hydrological station is especially important for the part of river from the village Kamičak (rkm 83) to the village Mrđenovci (rkm 95) which has a 180 cm deep and 24 m wide channel dug through when the level on Šabac hydrological station shows 0 cm.

Ships and pushed convoys need to pass this section with special attention while obeying all the norms of navigation. Each deviation from experience and valid rules can cause leaving the waterway, grounding of ships or parts of convoys, closing of the waterway, and even more severe accidents since the river bed on the sector of Kamičak is rocky.

On Lower Sava (with the exception of sector of Šabac as shown in Figures 2 and 3) maximal dimensions of pushed convoys which are navigating in the upstream and downstream direction are not limited and depend on temporary conditions on waterway and power of the propelling engines of pushboats.

Figure 3 - Šabac sector rkm 84 to rkm 78 [1]

river Drina into Sava (rkm 175), in the so-called Šabac sector. Research includes changes in water level on hydrological station Šabac, which is used for planning the navigation on this sector of Sava, both from view point of low navigation levels and and high navigation levels. This is because low water levels on Sava are

limiting factor for draught of ships and barges in pushed convoys, while high water levels limit the height of highest point of the ship-pushboat. This is the reason why it is necessary to determine navigation characteristics of river Sava on Šabac sector, especially from the view point of determination of actually possible draughts of ships and barges.

The research of water levels on Lower Sava sector for hydrological station Šabac has been done for the period between the 1st of January 1962 to the 31st of December 2013. To obtain the most precise state in the waterway on this part of the river Sava, from the view point of navigation of ships with large draughts, during the starting point of research was the assumption that the possible depth of waterway in Šabac sector is $H=180$ cm [1] when water hydrological station Šabac shows 0 cm, or in other words depth $H<180$ when hydrological station shows negative values.

$$H = h_v + 180 \quad (1)$$

where the following are:

H – possible depth of waterway on Šabac sector, cm;

h_v – measured (current) water level at hydrological station Šabac, cm.

Besides that it is known that minimal depth of waterway for safe navigation (H_{min}) is calculated according to the following expression:

$$H_{min} = T_{max} + h \quad (2)$$

where the following are:

T_{max} – maximal draught of ships or barges in pushed convoy, cm;

h – spare depth, which is the distance from the river bed and ship's hull, m; for ships and pushed convoys travelling at relatively low speeds spare depth is 30 cm.

From the expression (2) it follows that maximal draught of ships and barges is:

$$T_{max} = H_{min} - 30 \quad (3)$$

Based on expressions (1), (2) and (3) the expression for determination of the possible draught of ships and barges T_e (cm) while navigating through Šabac sector can be written as:

$$T_e = h_v + 180 - 30 = h_v + 150 \quad (4)$$

Figure 4 shows the change in water levels for the hydrological station Šabac, for each year of the observed period between the 1st of January 1962 to the 31st of December 2013 together with its average value with standard deviation (s) added and subtracted, while

figure 5 shows average possible draughts for the same period with standard deviation added and subtracted from the average value determined from water levels for the observed period calculated according to the expression (4).

Figure 4 - Graph of the changes in water levels for the observed years for hydrological station Šabac (Source:Authors)

Figure 5 - Graph of the changes of possible draughts of ships or barges for the observed years for hydrological station Šabac (Source:Authors)

Figure 6 – Probability of changes of possible draughts of ships and barges for the hydrological station Šabac (Source:Authors)

Figure 7 – Expected number of days for navigation for the hydrological station Šabac (Source: Authors)

Figure 6 presents probability of changes of possible draughts of vessels (P_T) in the Šabac sector of river Sava and figure 7, according to the same principle presents expected number of days for the navigation of vessels with known draught (P_d) for the same sector. International waterway of the IV class should provide navigation for ships of the following dimensions: length $L=80-85$ m; beam $B=9,5$ m; draught $T=2,5$ m, as well as to pushed convoys of dimensions $L_{max} \times B \times T=85 \times 9,5 \times 2,5-2,8$ m (Škiljaica, Čolić, 1998). For example, for hydrological station Šabac, for the value of the vessels draught of $T \leq 250$ cm probability for the use of the given draughts is $P_{T \leq 250} \geq 0,6981$ while expected number of days for navigation is 254,79 days, for the value of the vessels draught $T \leq 280$ cm $P_{T \leq 280} \geq 0,6536$ and expected number of days for navigation is 238,58 days, while for the value of the vessels draught $T \leq 300$ cm $P_{T \leq 300} \geq 0,62$ and expected number of days for navigation is 226,31 days.

3. UTILIZATION OF SHIPS CARRYING CAPACITY

In the system of water transport ships have main productive role. This is the reason why it is necessary to direct the organization of ship's work towards more efficient use of ships and perfecting of methods for management of transport processes. Besides that, exploitation of ships in transport processes must be organized in such a manner which for given conditions provides the highest possible productivity of ships. One of the ways to determine the utilization of ships from a transport fleet and analyze their work is calculation of real values of exploitation parameters of each individual ships or for group of ships. For the purposes of this paper the utilization of ship's carrying capacity (ε) is determined based on calculated depths on the Šabac sector.

Calculation of the utilization of ship's carrying capacity (exploitation parameter of load, load coefficient and static coefficient of utilization are some of other names for this parameter) is done according to the expression (5) [11], [12]:

$$\varepsilon = \frac{Q_e}{Q_r} = \frac{\sum Q_e}{\sum Q_r} \quad (5)$$

where the following are:

Q_e – really loaded amount of cargo in a vessel, t;

$\sum Q_e$ – really loaded amount of cargo in all the vessels that create pushed convoy, t;

Q_r – registered carrying capacity of one ship for transport of cargo, t;

$\sum Q_r$ – registered carrying capacity of all the ships for transport of cargo that create pushed convoy, t;

It is obvious that with the change in water levels (as presented in the figure 4) conditions for navigation of ships change on daily bases, which is the reason why it is necessary to constantly adjust draughts of ships navigating through Šabac sector. Since the carrying capacity of ships or barges depend on their draught $Q_e = f(T_e)$, this circumstance, at the same time, changes of the really loaded amount of cargo in one vessel or all the barges that create pushed convoy $\sum Q_e$. At (real possible, daily) draught T_e carrying capacity of ship is determined by applying the rule of linear interpolation, according to the expression (6) [13]:

$$Q_e = Q_r - q \cdot (T_r - T_e) \quad (6)$$

where the following are:

T_r – registered (maximal) draught of cargo ships, m;

T_e – (real possible) draught of cargo ships, m (expression 4);

q – specific carrying capacity of cargo ship per 1 m of draught, t/m, calculated according to the expression (7) [13]:

$$q = \frac{Q_r}{T_r - T_0} \quad (7)$$

where T_0 – is the minimal draught of ship (draught of empty ship), m.

Based on expressions (5) and (6), for known ship types, utilization of ship's carrying capacity (ε) can be determined. This paper examines the change of this parameter according to the given method for several characteristic barge types which are being used and whose draughts are 220, 230 250 and 260 cm respectively.

Figure 8 shows periods of limited values of carrying capacity-parameter of the utilization of ship's carrying capacity (ε) for stated barge types (draughts from 220 cm to 260 cm) within a year based on analysis of water levels on the hydrological station Šabac for the observed period between the 1st of January 1962 to the 31st of December 2013.

Figure 8 - Diagram of change of parameter of the utilization of ship's carrying capacity (ε) for different ship draughts

Periods of limited carrying capacity of ships and barges based on utilization of ship's carrying capacity (ϵ) are presented in the table 1.

Table 1. Expected periods of limited carrying capacity of ships

Draught (cm)	Expected beginning of the period	Expected end of the period	Expected duration of period (days)
220	11.08.	31.08.	21
230	05.08.	18.09.	45
250	23.07.	22.09.	62
260	21.07.	01.10.	73

Described method of linear interpolation, for known values of Q_r , T_r and T_0 , specific carrying capacity (q) is calculated for several barge types with draughts as in the table 1. Table 2 presents basic

Table 2. Carrying capacity as a function of draught

Barge type	Q_r (t)	Expressions for calculation of exploitation carrying capacity Q_e (t) according to expresion (7)	Maximal theoretical amount of transported cargo for one year ΣQ_e (t)
JRB71700	1598,75	$Q_e = 787,561 \cdot (T_e - 0,47)$	570.744
PIM71780*	1538,20	$Q_e = 735,9808 \cdot (T_e - 0,51)$	544.587
HP71760*	1455,20	$Q_e = 731,256 \cdot (T_e - 0,51)$	519.263
DL71360	1340,16	$Q_e = 698,00 \cdot (T_e - 0,38)$	485.415
BBP77400*	730,83	$Q_e = 415,244 \cdot (T_e - 0,44)$	265.836

Note: * – symmetric barge; JRB – Jugoslovensko Rečno Brodarstvo, Belgrade; PIM – „Ivan Milutinović“ company, Belgrade; HP – "Heroj Pinki" company, Novi Sad; DL – "Dunavski Lloyd", Sisak; BBP – Bagersko Brodarsko Preduzeće, Belgrade

Barges with higher carrying capacities achieve higher transport work per year in comparison to those with lower carrying capacities. For example JRB71700 barge can achieve 2,15 times more transport work than BBP77400.

4. CONCLUSION

There is no doubt in the significance of the river Sava as a transport corridor for the whole region through which it flows. Its connection to the Danube provides opportunity for the economy to exit and to connect the region to Danube countries and countries of Western Europe, Ukraine, Russia, Turkey and countries of the Middle East. Having in mind hydrological characteristics of river Sava it is possible to organize the work of cargo ships in such a manner to maximally utilize their carrying capacity at each moment.

It is obvious that on the Lower Sava sector low water levels appear along with extremely low water levels which limit or stop navigation all together. This

characteristics of the barges that have been used for analysis. Based on given parameters the expressions for determination of the possible amount of cargo that can be loaded into ships have been determined for barges of certain type (Q_e), by mathematical model of straight line through two points where the first point is (T_0 ; 0) and the second one (T_r ; Q_r). Expressions for calculation of exploitation carrying capacity (Q_e) of several barges types present on river Sava are also shown in the table 2. By applying these expressions, and based on the change of possible draughts of vessels within a year, maximal theoretical amount of transported cargo (ΣQ_e) can be calculated, under the assumption that through Šabac sector one barge (ship) of observed type is passed through per day, by summing all the values of carrying capacities (as a function of change of draught) for one year. These values are also presented in the table 2.

is the reason why this paper shows the procedure for calculation of possible values of draughts for different types of vessels during navigation through the hardest section of Lower Sava so called Šabac sector, which is characterized by its shape and dimensions. The paper fulfilled its goal which was to, based on determined calculation procedure, calculate possible draughts of ships or barges in convoy on this sector during periods of limited navigating conditions.

Procedure for determination of the periods of limitations in draughts is based on analysis of change in water levels for large number of years, by using nautical norms stated periods are determined, which is shown on separate diagram. At the same time analysis of the change of the utilization of ships carrying capacity (ϵ) of ships with different draughts, which was also shown on separate diagram. In such a manner period of a year when ships or barges can achieve best results in exploitation is determined and presented. It is obvious that with the increase of draught there is also increase in number of days when the parameter of

utilization of ships carrying capacity achieves values $\varepsilon < 1,0$. This paper also presented graphs and expressions for calculation of probability of change in possible draughts of vessels and expected number of days for navigation with set draughts. Based on these expressions it can be established that barge (ship) whose maximal draught is $T \leq 250$ cm has expected number of days for navigation 254,79 while probability of appearance is $P_{T \leq 250} \geq 0,6981$, for vessels draught $T \leq 280$ cm $P_{T \leq 280} \geq 0,6536$ and expected number of days for navigation is 238,58 days, while for vessels draught $T \leq 300$ cm $P_{T \leq 300} \geq 0,62$ and expected number of days for navigation is 226,31 days. Also by using expressions shown in the table 2 it is possible to determine maximal theoretical amount of transported cargo (ΣQ_e) that can be transported in one year, under the assumption that through Šabac sector one barge (ship) of observed type is passed through observed sector per day. Based on established values in such a manner it can be concluded that it is better to use barges with higher carrying capacities which are loaded with less cargo during periods of limited draughts compared to barges with lower carrying capacities during the whole year should the analysis of incomes and costs justify such exploitation principle for ships and barges.

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SUMMARY

ANALIZA PLOVIDBENIH KARAKTERISTIKA NA DONJOJ SAVI U CILJU UTVRĐIVANJA GAŽENJA BRODOVA

U radu biće predstavljen postupak za proračun moguće veličine gaženja potisnica u potiskivanom sastavu prilikom prolaska kroz pojedine delove Donje Save koji se odlikuju svojim karakterističnim oblikom i dimenzijama. Cilj rada je da se, na osnovu poznatih računskih postupaka, utvrdi veličina mogućeg gaženja za prolazak brodova ili potiskivanih sastava kroz ovaj sektor pri ograničenim plovidbenim uslovima, zbog utvrđivanja perioda u toku godine kada brodovi ili potiskivani sastavi mogu da ostvare najbolje rezultate u eksploataciji.

Ključne reči: brod, potiskivač, potisnica, plovidba, vodostaj, ograničena dubina, ograničeno gaženje