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Conceptual Nautical Dimensions for Paraguay River Waterway Amelioration Works in Critical Stretches (Brazil)

J. P. Alves Sanchez & P. Alfredini
Polytechnic School of São Paulo University, São Paulo, Brazil

ABSTRACT: The Paraguay River Waterway is a crucial axis for integration in South America, with a course of 3.442 km from Cáceres (Brazil) to Nueva Palmira (Uruguay). To provide the navigation, improve the safety, the reliability and efficiency of the waterway transport, for a minimum period corresponding to 90% of the year, interventions with amelioration works are necessary. Among them, dredging in critical stretches stand out, which currently present some form of obstacle to navigation, either by natural factors (widths, radius of curvature and depths) or by structures, such as bridges, and sand shoals. This paper proposes a reassessment of the current nautical dimensions based on new guidelines, assessing critical sections for depth, width, and radius of curvature. The aim is to increase safety and study the feasibility of expanding the waterway by accommodating larger convoys.

1 INTRODUCTION

According to the Strategic Plan for Brazilian inland navigation [1] there is a significant underutilization of the inland waterway, as only 5% of cargo is currently transported by this mode. However, there is evidence of a potential for growth from 27 to 120 MTPY (Million Tons Per Year) from 2016 to 2031. With a river network of 42,000 km of potentially navigable waterways, only about 20,000 km are currently used for navigation, exposing the weak national development in this kind of transport. [2]

The Paraguay River originates in the interior of the South American continent, in the Municipality of Cáceres (Mato Grosso State - MT) and has its course following North-South direction, up to Nueva Palmira (Uruguay). The Brazilian stretch is approximately 1.270 km long, between Cáceres (MT) and the mouth of Apa River, being subdivided into North Section – in light blue – and South Section – dark blue – as shown in Figure 2. The waterway provides a direct link between the Brazilian Midwest and the Atlantic Ocean. Agriculture, mainly focused on soybeans and livestock, is also a significant activity that uses the main ports in Cáceres (MT) and Porto Murtinho (Mato Grosso do Sul State - MS). Among the challenges presented in navigating this section, the main difficulty is the depth in some of its critical stretches.

The North Section is generally a region of low navigational potential. The area south of Cáceres has low depths during the dry season but the navigational conditions improve as the Paraguay River approaches the city of Corumbá (MS), where it widens, and the number of sand shoals decreases. Navigation on this section is currently not very expressive, consisting mainly of tourist vessels. The minimum depth established is 1.80 m and the design convoy is made up of 6 barges, in the 2x3 configuration.

Figure 1. South America continent with Paraguay Waterway area highlighted.

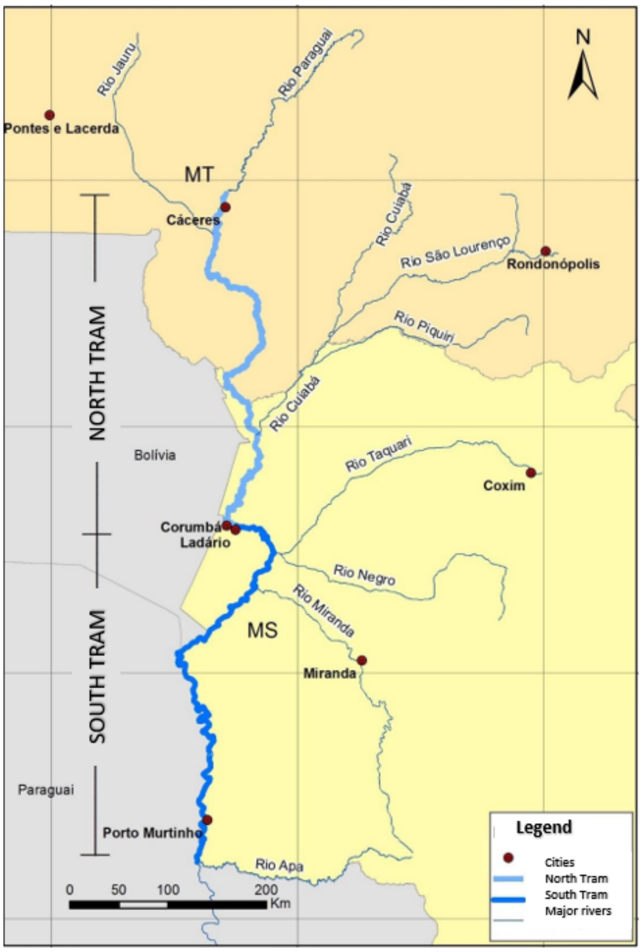

Figure 2. Paraguay Waterway - Brazilian stretch. [3]

The South Section is about 590 km long and has some artificial obstacles, including Eurico Gaspar Dutra railway bridge. Currently, this route carries most cargo transported by the waterway. The annual throughput in 2022 was of 4.2 MTPY, subdivided in: 3,9 MTPY of iron ore, 0.3 MTPY in soybean, 0.02 MTPY of sugar and 0.01 MTPY of iron and steel. The minimum depth adopted is 3.0 m, with standard convoys of up to 16 barges, in the 4x4 configuration.

The objective of this paper, which focuses on shallow draft navigation (typically less than 5.0 m in depth) in unchanneled rivers, is to carry out a conceptual evaluation of the nautical dimensions of Paraguay River Waterway in Brazilian territory, using PIANC guidelines [4]. The critical dimensions, such as depth, width, radius of curvature, and bridge openings, are identified with regards to the design vessels.

From 117 critical stretches [5,6] (shallow areas and tight curves) identified – counting North and South Sections – the 47 critical stretches of South Section were assessed, considering the dimensions of suggested design convoy with safe navigation. In addition, to assess the necessary amelioration works to guarantee navigation with the recent classification according to PIANC guidelines [4], the works must aim to ensure the navigation of convoys for a minimum period corresponding to 90% of the year, consisting essentially of dredging.

Currently, it is important in Brazil to apply the state of art about guidelines for the inland waterways' dimensions design, as recently published by PIANC [4] and, in this sense, adopt updated knowledge in tune with the modernization in the vessel fleet, especially with the growing number of longer, wider and with large draft vessels.

According to [7], from a broad point of view, the use of inland waterway systems in the region is hindered by several factors, including:

- Incomplete, outdated, or missing national and regional regulatory standards;
- Lack of a common basis for the classification of waterways in South America for the navigation protocols standardization at national and regional levels;
- Lack of standardization, vessel and control procedures;
- Lack of investment in construction and maintenance of waterway infrastructure and river ports;
- Weak administrative structures and delays in building institutional capacity, especially with regard to human and financial resources;
- Absence of navigation aids, including up-to-date maps, electronic charts, signals and other navigation services;
- Inadequacy of qualified personnel and institutions for training and training highly qualified professionals.

The hinterland of the Paraguay River Waterway is in full expansion within the agro-industrial and mining market. Maize export is estimated to grow from 15.89 MTPY to 41.50 MTPY from 2015 to 2030 and soybeans are projected to grow from 12.42 MTPY to 28.75 MTPY for the same period. [3]

With the increased demand for handling these loads, it would even be feasible to study the use of self-propelled vessels [8]. The use of these vessels would increase the logistical efficiency of supply chains and could replace other transport used, such as road and rail. However, the replacement of the fleet by larger vessels requires a reassessment of sections to ensure their good navigability.

Based on a possible evolution of the fleet, the development of inland waterway will enable new businesses, such as the transport of Bolivian liquefied gas, which would allow delivering this product to end consumers where geographic, demographic, or environmental specificities do not allow the use of traditional means. [9]

2 CRITICAL POINTS DESCRIPTION

To carry out the assessment of critical stretches, a database composed mainly of fluvial charts from Brazilian Navy was used, which allowed the characterization of 47 South Section critical stretches. After selecting fluvial charts corresponding to the critical stretches, the geometric data were read, followed by the conceptual model elaboration with the bathymetric information incorporated in the drawings. The models created are digital terrain surfaces that contain the isobaths and morphology of chosen sections. It should be noted that these models created have a certain degree of imprecision, as they are not intended for design purposes, but for qualitative and conceptual analysis of the terrain.

Figure 3 shows an example of the bathymetric information contained in the nautical chart and the digital terrain model built in the Civil 3D software for M'Bigua stretch.

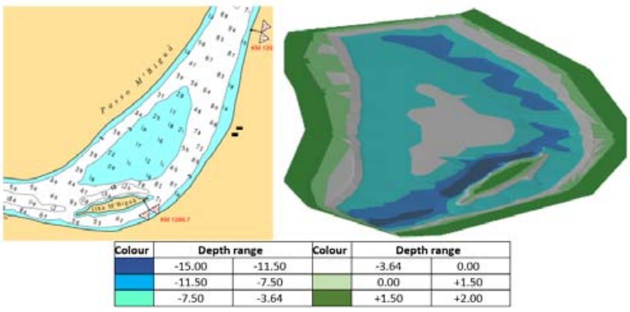

Figure 3. Nautical chart and digital terrain model of M'Bigua critical stretch.

3 CURRENTLY NAUTICAL DIMENSIONS

For a waterway to be considered navigable, it is necessary that planialtimetric nautical dimensions are satisfied, to guarantee the safe and free traffic of the design vessels adopted. In sections that do not naturally fit safe dimensions, works to improve the river channel are necessary, which are often dredging to adapt the geometric design.

The Brazilian Waterways Classification is currently based on DNIT - National Department of Transport Infrastructure - guidelines [10]. The classification for Brazilian waterways is a function of beam dimensions (B) and length (L) of the design vessel and includes a parameter for minimum operational depth (P) of the waterway (Table 1 and Table 2).

Table 1. Waterway classes according to the design vessel beam and length [10].

Class	B (m)	L (m)
I	48.0	280.0
II	33.0	210.0
III	25.0	210.0
IV	23.0	210.0
V	16.0	210.0
VI	16.0	120.0
VII	12.0	140.0
VIII	12.0	80.0
IX	12.0	50.0

Table 2. Waterway subclasses according to the design vessel draft [10].

Category	P (m)
Special	> 3.50
A	3.50
B	3.00
C	2.50
D	2.00
E	1.50
F	1.00

The width of waterway is determined through following equations:

One lane traffic: $W_1 = 2.2\ B$

Two-lane traffic: $W_2 = 4.4\ B$

Although there is no guideline for calculating the channel width at apex of curves, the section where the maximum width occurs, in practice it is calculated by:

$$W_c = W_F + \frac{L^2}{2R}$$

where:
W_c is the maximum channel width in the apex of curve;
W_F is the channel width in a straight reach;
L is the design vessel length;
R is the radius of the curve.

Finally, other design criteria include:
- The curve is defined with radius interval between 4 and 10 times the design vessel length;
- The distance between consecutive curves must be at least 5 times the design vessel length;
- Dredging sites require side slopes of 1:8 for alluvial channels;
- Rock excavation sites require side slopes of 1:1.

The 4x4 and 5x5 design convoys that navigate in the southern tram of Paraguay River Waterway have the following geometric characteristics, respectively:

- B_{4x4} = 48 m; B_{5x5} = 60 m
- L_{4x4} = 290 m; L_{5x5} = 360 m
- T_{4x4} = 2.6 m; T_{5x5} = 2.6 m

For Paraguay River Waterway South Section, the minimum DNIT guidelines recommended for nautical design in the currently conditions are the dimensions given in Table 3.

Table 3. Paraguay River Waterway South Section recommended nautical dimensions (DNIT guidelines).

Depth (m)	Width (m)	Radius (m)
3.00	105.6	1,160 – 2,900

DNIT criterion, although published in 2016, is based on European guidelines from the 1950s and adopted for self-propelled vessels. This shows the need to present most recent guidelines regarding transport and river dynamics, justifying the adoption of most recent PIANC guidelines [4], comparing classifications and verifying the possibility of improve navigation in critical stretches.

4 PIANC GUIDELINES [4]

PIANC Working Group InCom WG 141, motivated by the lack of international guidelines, sought to establish a systematization for the minimum dimensions of inland waterways. It includes guidelines for width, depth, draft and headroom for boat and ferry traffic, as well as guidelines for safe navigation, the environment, and other practical considerations. This paper was limited to assess the main geometric design parameters: minimum width, depth, and radius of curvature.

PIANC guidelines [4] compared a trapezoidal profile in canals and rivers of several countries, including China, Netherlands, France, Germany, Russia, and United States. From ratios W_F/ B and h/T (depth to draft) of existing waterways and relating them to navigation quality of each channel – where A is almost unrestricted navigation; B Moderately to severely restricted navigation; C strongly restricted navigation over short distances – it was possible to elaborate Table 4 for the Paraguay River Waterway, which shows the values for minimum width, depth and radius of curvature for each adopted quality classification.

Regarding the minimum depth of channel, a 1.3 times of draft ratio is proposed. This value ensures good drive quality, with sufficient under keel clearance in shallow water and can be reduced to the but should not be less than 1.2. In this case, the designer must define under keel clearance, which depends on the river bottom nature, as well as the type and vessel equipment. The following aspects must be considered:

- The squat increases with vessel speed relative to the water. Thus, easy navigation at high speeds requires sufficient under keel clearance;
- As depth/draft ratio decreases, the vessel speed used tends to be reduced. Therefore, a minimum dynamic sink of 0.20 m should be considered, which generally allows for sufficient speed in shallow water;
- In case of the speed reduction mentioned in previous item, this can lead to large widths, especially in cross current fields and to consider wind influences, but also in curves on a downstream navigation;
- If the channel width cannot be increased, a minimum extra under keel is required for safe navigation, increasing the minimum from 20 cm to 40 cm, in case of solid rock on the river bottom, 50 cm for bottom on gravel and 50 cm for fully effective bow thruster.

Compiling the considerations and criteria briefly described the Working Group proposed three classes of navigation quality, based on the channel dimensions and vessel type. In Table 4 are presented the minimum PIANC guidelines [4] recommended for nautical design characteristics in the currently conditions.

Table 4. PIANC guidelines [4].

Waterway	Fairway width for alternate single-lane			Remarks
	Easy quality C	B	A	
Min W_F (straight sections) (m)	3 B = 144 2.8 B = 134.4	3.2 B = 153.6	3.4 B = 163.2	For security reasons
Min h (over entire fairway width) (m)	1.2 T = 3.12	1.3 T = 3.38	⩾ 1.3 T = 3.64	Due to squat & efficiency of bow-thrusters
Min R (m)	2 L = 580	3 L = 870	4 L = 1,160	Depending on natural condition

5 EXTRAPOLATION FOR 5X5 CONVOYS

The largest convoy navigating Paraguay River Waterway operates in the downstream section, between Santa Fe (Argentina) and Nueva Palmira (Uruguay). The section is fluvio-maritime and comprises convoys with 5x5 formation, with a load capacity of up to 40,000 DWT [11]. The use of this maximum transport capacity in the Brazilian section would lead to changes in classifications of South Section critical stretches, in terms of width and radius.

6 AMELIORATION WORKS

The last stage of this study was to verify the amelioration works necessary quantitative and qualitatively for critical stretches to be classified in category A – as much as possible for the three variables – for current navigation (according to [4]). In addition to inferring what additional works would be necessary to enable critical stretches for navigation of 5x5 type convoy, which already navigates the stretches under Paraguayan and Argentine jurisdiction further south of waterway.

Amelioration works services can be summarized as dredging and demolition services, the first being the most important due to the riverbed nature.

Dredging is the process of removing sediment, sand, mud, and other materials from the bottom of water bodies to maintain adequate depths for navigation and ensure navigation safety. Additionally, is performed using a variety of techniques and technologies, including mechanical dredges, suction dredges, and hydraulic dredges. The choice of dredging technique will depend on various factors, including location, depth, and the nature of material to be removed.

Demolition is an activity that involves removing rocks and stones from the floor to deepen navigation channels or for other purposes. This activity is important for ensuring the safety and efficiency of navigation.

7 RESULTS

7.1 *DNIT x PIANC guidelines [4] for current navigation*

Table 5 displays the classification of the 47 critical stretches studied in South Section, with respect to width, radius, and depth, for both criteria adopted in this study. Following the assessment, graphs were constructed grouping the classifications for each geometric variable of the navigable channel.

Figures 4 to 8 show the percentages of the 47 selected critical stretches that fit each classification for the current type of convoy (4x4) and for a future phase of the waterway (5x5 convoy), with the purpose of verifying the feasibility of a possible waterway expansion.

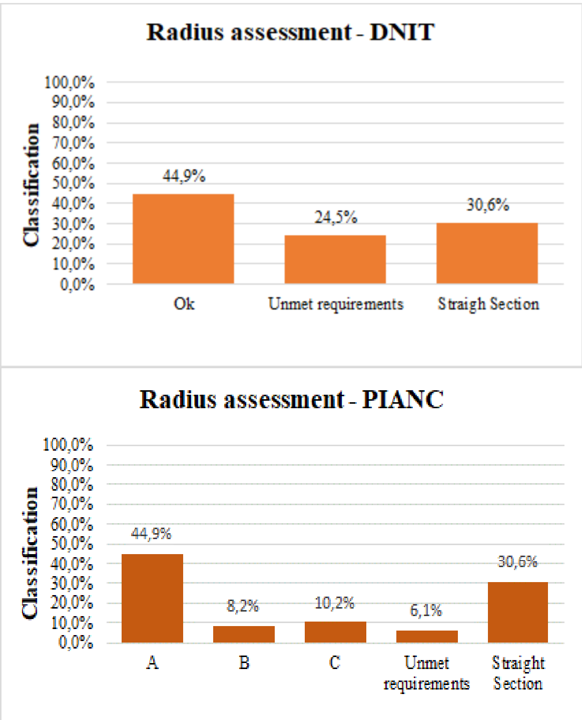

Figure 4. Verification of the sections regarding radius criteria.

It appears that according to DNIT guidelines 24.5% of critical stretches do not meet the minimum requirements for radius of curvature proposed, but according to PIANC guidelines [4], a smaller number of stretches does not meet the minimum bending radius requirements (6.1%).

Table 5. Comparison of DNIT and PIANC guidelines [4].

Critical Stretches	DNIT			PIANC		
	W	R	D	W	R	D
Close to Republica Island	Ok	SS	Ok	UR	SS	A
Porto Sastre	Ok	UR	Ok	UR	B	A
Close to Cancha Estrela	Ok	SS	Ok	A	SS	A
Boca inferior riacho Celina	Ok	UR	Ok	A	UR	A
Close to Porto Murtinho	Ok	UR	Ok	UR	C	A
Tarumã	Ok	Ok	Ok	A	A	A
Fecho dos Morro Islands	Ok	Ok	Ok	UR	A	A
Camba Nupa	Ok	SS	Ok	A	SS	A
Barranco Branco	Ok	UR	Ok	A	B	A
Olimpo	Ok	Ok	UR	A	A	UR
Furado do Nabileque	Ok	UR	UR	C	UR	UR
Curuçu	Ok	SS	UR	A	SS	UR
Braga Island	Ok	SS	Ok	A	SS	A
From Rabo de Ema Island to Spinello Island	Ok	Ok	Ok	A	A	A
Porto Mirhanovich	Ok	UR	Ok	UR	UR	A
Alegrete Inferior	Ok	Ok	Ok	A	A	A
Alegrete Superior	Ok	SS	Ok	A	SS	A
Close to Nu Guazu Farm	Ok	Ok	UR	A	A	UR
Periquitos	Ok	Ok	Ok	A	A	A
Porto Esperanza	Ok	SS	Ok	A	SS	A
Cururu	Ok	Ok	Ok	A	A	A
Baía Negra	Ok	Ok	Ok	A	A	A
Negro River	Ok	Ok	Ok	A	A	A
Isla del Sauce	Ok	Ok	UR	A	A	UR
Santa Rosa Island	Ok	Ok	UR	A	A	UR
Close to Santa Fé Island	Ok	UR	Ok	B	C	A
Porto Bursh	Ok	Ok	Ok	C	A	A
M'Biguá	Ok	Ok	UR	A	A	UR
Rebojo Grande	Ok	SS	Ok	A	SS	A
Paratudal	Ok	Ok	Ok	A	A	A
Close to Primavera Farm	Ok	UR	UR	A	C	UR
Piuvas Inferior	Ok	UR	Ok	A	C	B
Piuvas Superior	Ok	SS	Ok	A	SS	A
Volta da Ferradura	Ok	UR	Ok	A	C	A
Close to Morro do Conselho	Ok	UR	Ok	A	B	A
Close to Bugio Island	Ok	UR	Ok	A	B	A
Close to Rio Branco Bridge	Ok	Ok	Ok	A	A	A
Close to Nossa Senhora do Pantanal Bridge and Jacaré	Ok	Ok	Ok	A	A	A
Caraguatá	Ok	SS	UR	B	SS	UR
Close to Cambará Ferrado Island	Ok	Ok	Ok	B	A	C
Abobral	Ok	SS	Ok	A	SS	A
Close to Porto da Manga	Ok	SS	Ok	A	SS	A
Close to Taquari River	Ok	Ok	Ok	A	A	A
Macunã	Ok	SS	Ok	A	SS	A
Close to Tira Catinga Island	Ok	SS	Ok	A	SS	A
Volta Miguel Henrique	Ok	Ok	Ok	A	A	A
Santana or Jatobá	Ok	Ok	Ok	C	A	A

W – Width
R – Radius
D – Depth
SS – Straight section
UR – Unmet requirement

According to nautical charts, 18.4% of the critical stretches have insufficient average depth for navigation both by DNIT guidelines and PIANC guidelines [4](Figure 5), resulting in a loss of operational efficiency.

Unlike DNIT guidelines, in which the minimum width is 105.6 m, resulting in 100% approval of critical stretches, PIANC guidelines [4] is more demanding with regard to the minimum width of the navigable channel. Thus, 10.20% of critical stretches do not meet the criterion (Figure 6).

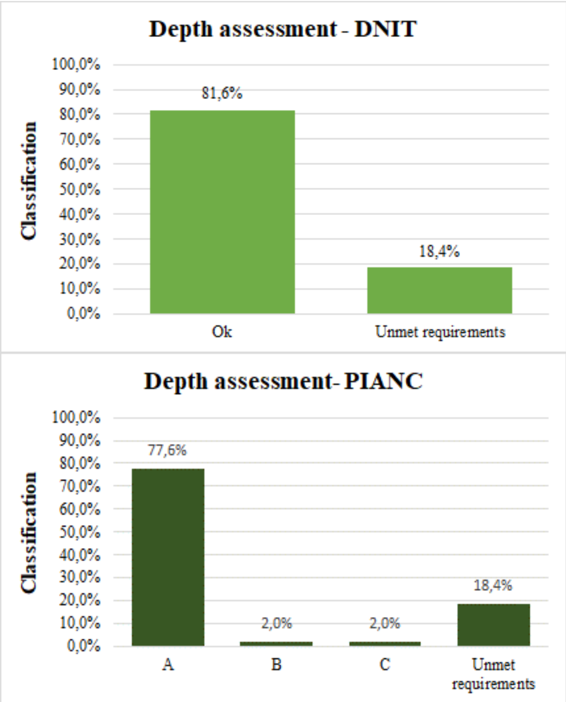

Figure 5. Verification of sections regarding depth criteria.

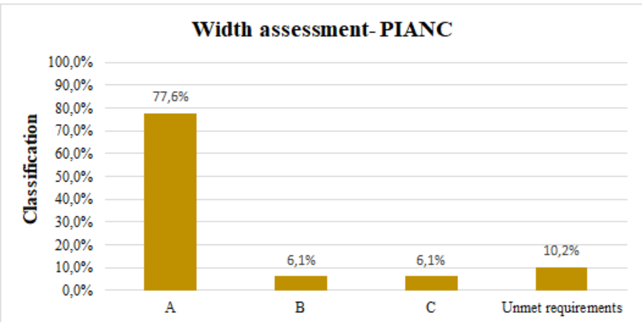

Figure 6. Verification of sections regarding the width criteria.

7.2 *Amelioration works for current navigation according to PIANC guidelines [4]*

After modelling all critical stretches, it was possible to create cross sections to obtain the width of each section navigable range, setting the minimum depth to 3.64, which is A rating, according to PIANC guidelines [4].

The calculation of the dredged volume was performed with the help of the Autodesk Civil 3D software in which 3D surfaces are constructed, one with the elevations and morphology of the existing channel and the other with the elevations and geometry of the proposed channel, and subtracted from each other, resulting in a surface that carries – in the context of the study – the volume to be dredged to obtain the proposed channel.

Table 6 summarizes results obtained from the dredging quantities for selected critical stretches, corresponding to a total volume of 15,345,375 m³. Considering only a sample of the critical stretches marked by *, the dredging volumes needed would be 1,435,676 m3, while employing the DNIT guidelines the figure would be only 330,750 m3 (this last value obtained from [11]), that is 4.34 times more than the dredging currently made. This fact implies a constant attack on the banks of the river in the curved sections, due to insufficient works of dredging and highlights the need of adopting a safer design guideline regarding the criteria for sizing the waterway, like the recently published PIANC guidelines [4], according to each permitted convoy type.

7.3 *Extrapolation results for 5x5 convoys navigation*

For 5x5 convoys navigation, a survey of the sections was carried out according to PIANC guidelines [4] classification for width and radius. The results are shown in Figures 7 and 8.

Table 6. Dredging amelioration works quantitative summary.

Critical Stretches	Cut Volume (m³)	Mean dredging depth (m)	Mean channel elevation (m)
Close to República Island	609,946	0.97	-5.31
Porto Sastre	644,710	1.25	-3.85
Close to Cancha Estrela	103,385	0.18	-8.57
Boca inferior Riacho Celina	318,081	0.47	-7.58
Close to Porto Murtinho	411,960	0.63	-6.84
Tarumã	375,271	0.40	-6.62
Fecho dos Morros Island	419,646	0.59	-6.41
Camba Nupa	223,600	0.15	-6.14
Barranco Branco	368,547	0.55	-8.38
*Olimpo	175,023	0.39	-5.12
Furado do Nabileque	917,136	0.88	-5.06
*Curuçu	48,589	0.07	-4.05
Braga Island	254,195	0.33	-6.17
From Rabo de Ema Island to Spinello Island	111,873	0.25	-6.46
Porto Mirhanovich	585,448	0.64	-8.56
Alegrete Inferior	209,587	0.30	-7.63
Alegrete Superior	265,433	0.45	-9.40
*Close to Nu Guazu Farm	147,416	0.29	-7.27
Periquitos	616,308	0.56	-7.57
Porto Esperanza	140,259	0.33	-8.07
Cururu	120,027	0.27	-6.77
Baía Negra	194,579	0.37	-7.05
Rio Negro	207,707	0.48	-6.77
*Isla del Sauce	189,677	0.32	-5.98
*Santa Rosa Island	186,664	0.27	-5.36
Close to Santa Fé Island	168,060	0.20	-5.43
Porto Bursh	870,958	0.85	-4.59
*M'Biguá	67,839	0.22	-4.90
Rebojo Grande	362,183	0.87	-7.60
Paratudal	422,943	0.86	-5.01
*Close to Primavera Farm	284,663	0.25	-6.39
Piuvas Inferior	243,449	0.43	-4.89
Piuvas Superior	133,350	0.16	-7.33
Volta da Ferradura	324,488	0.24	-8.53
Close to Morro do Conselho	329,714	0.40	-8.71
Close to Bugio Island	865,396	0.77	-7.53
do Jacaré + Rio Branco Bridge	192,500	0.22	-6.32
Close to Nossa Senhora do Pantanal Bridge	31,909	0.15	-8.11
*Caraguatá	379,805	0.97	-3.95
Close to Cambará Ferrado Island	704,333	1.09	-4.23
Abobral	49,612	0.12	-7.57
Close to Porto da Manga	103,870	0.15	-7.79
Close to Taquari river	36,469	0.19	-6.55
Macunã	50,893	0.17	-5.14
Close to Tira Catinga Island	36,767	0.08	-6.23
Volta Miguel Henrique	1,092,585	0.78	-7.07
Santana or Jatobá	748,522	0.59	-6.95

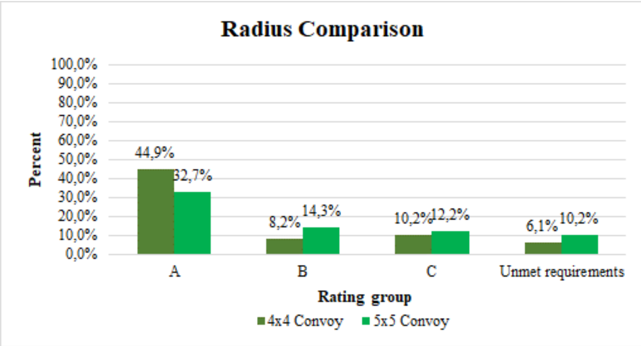

Figure 7. Radius criteria comparison.

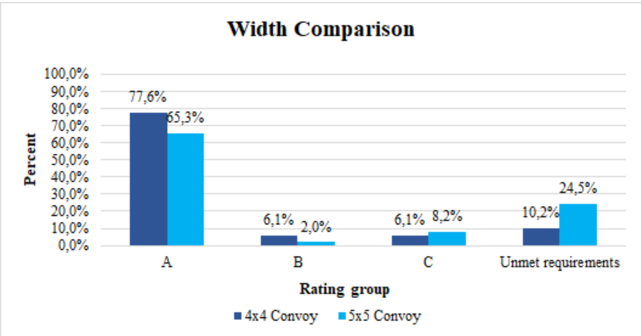

Figure 8. Width criteria comparison.

Observing the graphs, it is possible to verify that there would be an increase of 4.1% in stretches that do not meet the minimum requirements in terms of the minimum radius and of 12.2% in terms of width. In addition, for both variables, there is a decrease of 12.2% in sections classified as A.

7.4 *Dredging volumes comparison*

The results of dredging volumes in each section to allow navigation of the current convoy (4x4) in class "A" of PIANC guidelines [4] and the volume verification to make it navigable in this same condition for the 5x5 convoy, can be exemplified by volumes obtained for Furado do Nabileque presented Table 7.

Furado do Nabileque does not meet the minimum requirements of DNIT and PIANC guidelines [4] for curvature radius and depth, as shown in Table 5 and fits the width criterion C of PIANC guidelines [4].

Table 7 shows the dredging volumes necessary to classify the stretch as "A" for the 4x4 and 5x5 convoys, 917,136 m³ in the first case and 2,755,307 m³ in the second case, with an increasing of 1,838,170 m³.

Table 7. Amelioration works for Furado do Nabileque.

Convoy	Mean dredging depth (m)	Dredged Volume (m³)	
4x4	-0.88	917,136	
5x5	-2.41	2,755,307	
	-1.53	1,838,170	Dredging increase

8 CONCLUSIONS

The potential of inland navigation in the Paraguay River Waterway lies not only in making better use of existing infrastructure, but also in expanding the network as a large part of the waterway system in South America.

The waterway can have a positive impact on the region, increasing the competitiveness of the countries involved, promoting trade and economic integration between nations and improving logistics for transporting goods. In addition, it can generate direct and indirect jobs, leverage infrastructure development and boost local tourism.

The implementation of new guidelines considering good global practices for waterways sizing and classification is fundamental and urgent for conceptual design of Brazilian waterways, since currently guidelines date back to practices from prior to the 1960s, based on European self-propelled vessels rather than push tow convoys. From that time, inland waterways research had enormous progress and many technological resources and equipment were adopted in the field of aids to navigation and in naval designs to improve convoys manoeuvring.

The choice to select Paraguay River Waterway allowed to evaluate the figures of dredging volumes for amelioration works of navigation and showed the enormous difference from currently practice if the figures recommended with recently published PIANC guidelines [4] would be adopted for the conceptual design, instead of outdated insufficient DNIT guidelines.

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