Uruguay – Brazil Inland Waterway Transportation System
Defining the Right Vessel

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Abstract

Within the frame of the MERCOSUR (South Common Market), one of the most important goals to achieve by its member states is a better cost effective international cargo transportation system. For this purpose the project of developing a commercial waterway linking the east region of Uruguay with the south of Brazil has been under study for a number of years now. Because of the high costs involved on the development of such waterway, the project has been indefinitely delayed. It is our intention to show an alternative way to reduce the present obstacles by using a budget oriented approach in order to determine the vessel best suited to use on the proposed waterway.

So far, every study related to the project has been focused on the amount of work needed to modify the environment in order to accommodate the hardware already available in the region. The conclusions show that the cost of opening and maintaining the required navigation channel is high enough to discourage investment; the added responsibility to take care of any environmental damage incurred during the building and/or operation of the waterway makes searching for a less costly and hazardous option an interesting challenge.

The proposed terminal on the Cebollatí River would be located at the heart of the Uruguayan rice growing region. Uruguay exports 90% of its rice production, being Brazil its biggest buyer. Wood chips and clinker are the other types of cargo considered to use the proposed waterway in route to either Brazil or to overseas destinations through the deep water port of Rio Grande.

Through the analysis of local data by a Geographical Information System, international regulations regarding inland waterways and shallow draught vessel characteristics, we seek to propose a cost efficient alternative to apply on this particular scenario.

Keywords: South America, MERCOSUR, Uruguay, Brazil, Inland Waterways, Shallow Water Transportation, GIS, Navigational Channels, Cebollatí River, Merín Lagoon.

1. Introduction

Traditional navigational channel design starts from focusing on the particulars of a certain vessel which is capable of loading a desired amount of a certain cargo. The reasons for the election of a model ship are usually the ones aiming at maximizing cargo capacity, meeting a certain budget on running costs or local ship availability. The facts of dredging and channel maintenance costs are sometimes oversimplified; as a result, the budget originally thought to suffice for the opening of a waterway may become too much for a starting company.

The Cebollatí River is located in Uruguay, South America and the section under consideration is the one located between the meridians 53°37.5'W and 53o48'W and between the parallels 33°09'S and 33°12.5'S. The river runs in a N-NE direction for 25.3 km between the old port of La Charqueada and its mouth on the Merin Lagoon. The terrain is part of the Merin Lagoon Plain which is characterized by its low lands. The gentle slope and low banks make the Cebollatí a high meandering river with moderately low depths which show a constant decrease at the area immediately adjacent to the Merin Lagoon.

In October 2001, the company "Compañía Fluvial y Lacustre Oriental" presented a project aimed to exploit the waterway to the Uruguayan government. The project included the construction of three cargo terminals located in the vicinity of the Gral. E. Martinez town 25.3 km upstream from the mouth of the river. The three terminals would be used for the storing, loading and unloading of, wood chips and clinker respectively [3].

The type of ship selected as a model to use on the waterway is a bulk carrier double hull self propelled barge with three or four covered holds and two propellers. The particulars are as follow:

- LOA: 95 m
- Beam: 15.5 m
- Depth: 4.75 m
- Max. Draught: 4.23 m
- No. of Holds: 4
- Speed: 7 kts

The total cost for the construction and maintenance of the channel designed to accommodate the model ship are shown on Table 01 and Table 02.

Table 01, Estimated Channel Opening Cost

Max. Allowed Draught	Volume (millions of m³)	Unit Cost (USD)	Total Cost (millions USD)
2.5 mt	1.50	1.35	2.30
2.0 mt	0.75	1.35	1.15

Table 02, Estimated Channel Annual Maintenance Cost

Max. Allowed Draught	Volume (millions of m³)	Unit Cost (USD)	Total Cost (millions USD)
2.5 mt	0.60	1.5	0.90
2.0 mt	0.42	1.5	0.63

The total costs shown above appear to have considerably slowed the development of the project and alternative solutions of the problem are currently under consideration.

It is our objective to determine the smallest ship capable of navigating the Cebollatí River under economical feasible conditions by studying the geomorphologic characteristics of the river's natural channel using ArcGIS® 9.1.

2. Data Preparation

For the writing of this paper, ArcView® 9.1 with the extensions Spatial Analyst® and 3D Analyst® was used. The extra tools Channel Tool (developed by Venkatesh Merwade), XTools Pro®, Hawth's Analysis Tools® and ET GeoTools® were also extensively used.
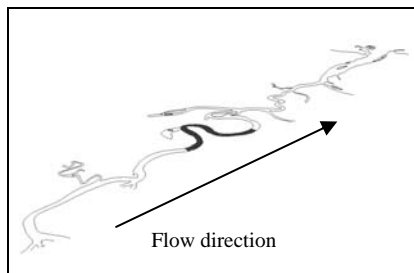

Fig. 01, River area of study

The depth points were digitized from a paper chart of the latest bathymetrical survey of the Cebollatí River done by the Hydrography Department of the Uruguayan Ministry of Transportation in 2002. The paper chart was scanned by sections and later assembled as a mosaic, rectified and georeferenced into a geotiff image by using the software Tatukgis Aerial Imagery Corrector® (AIC). The depth points were then extracted as a point shapefile with an elevation field attribute by doing a head up digitizing process on ArcView (Fig. 02). The projection used was Transverse Mercator with origin at 90°00.0'S, contact meridian at 54°48.0'W, 500000 m of false easting and Datum Yacare.
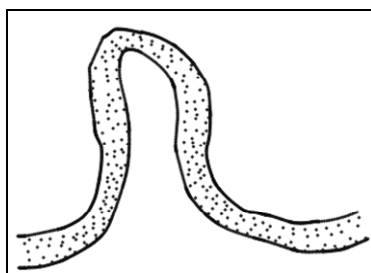

Fig.02, Depth points dataset

The depth of the points was originally referenced to the local

zero point at La Charqueada town which lies at +0.78 m from the national vertical reference plane. Because the river local level stays at a mean value of +1.45 m, the original dataset had values ranging from -9.2 m to +1.2 m. In order to be able to interpolate an accurate DEM, all the points were moved deeper by 1.5 m and the depths along the river banks equalized to 0 m. By doing so, the slope of the outer side at the meanders, curves back upwards to zero at the river bank instead of producing a "digital cliff".

A representative portion of the river was selected to test the using of the ArcGIS software to estimate reliable data. The section is 4750 m long and it comprises one of the curves with the smallest radius in the whole length of the river as well as showing a wide range of depths along its extension.

A Digital Elevation Model (DEM) of the riverbed was interpolated using the Topo To Raster function of the Spatial Analyst extension (Fig. 03). The tool is designed to produce a hydrologically correct interpolation of a stream of water. It requires a point shapefile of the bathymetrical data and a boundary polygon as input. The cell size of the desired resulting raster image affects the accuracy of the interpolation since it depends on the density of the depths point data. For this particular dataset, after several attempts with different cell sizes, a cell size of 9 m x 9 m was considered to produce the best interpolation image.
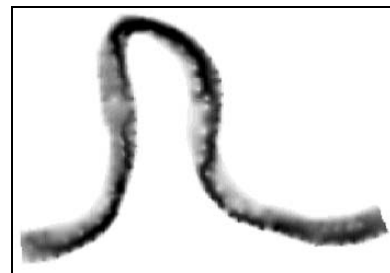

Fig. 03, Interpolated raster DEM

Once the DEM was obtained, a depth contour shapefile was generated using the 3D Analyst contour tool. The contours were calculated at intervals of 0.50 m to help us visualize the surface shape of the different depth planes. Using the contour shapefile as input, we generated a Triangular Irregular Network (TIN) of the data with the purpose of being able to estimate dredging volumes later.

The thalweg was located by using the Channel Tool extension [9]. This is achieved by the input of a centerline with equally spaced segments spanning along the length of the study area. Although Dr. Merwade advises that segments of 100 m are the most adequate to provide enough data points, it was very difficult to trace the acute curve of our river section. Thus, after several attempts with different sizes, the segments length considered to produce the most accurate thalweg for this case was found to be 70 m (Fig. 04).
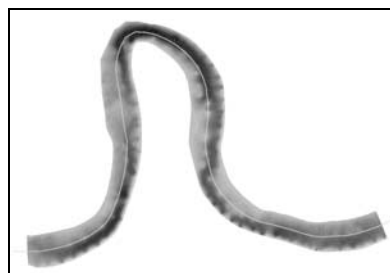

Fig.04, Input centerline with 70 m segments

The process of locating the thalweg is basically through the location of the deepest point on the line perpendicular to the input centerline at the segment's nodes. The depth information is obtained from the previously generated DEM. Once those points are determined, they are connected by a polyline ZM which is a line feature class with elevation and distance information (Fig. 05). A profile graph of the found thalweg is shown on Fig. 06.
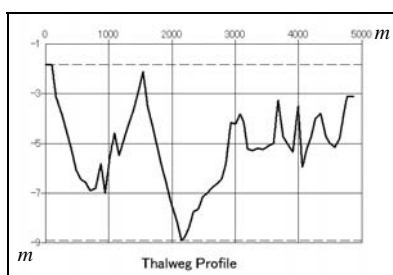

Fig. 05, Output thalweg as a polyline ZM

Fig. 06, Thalweg depth profile

3. Location of Cross Sections

In order to determine the channel cross sections, the Channel Tool assigns a new pair of curvilinear orthogonal coordinates (s.n) to the depth points as a new pair of attributes. "In the curvilinear orthogonal system, s is the distance along the centerline and n is the perpendicular distance from the centerline. The centerline runs in the direction of the flow. The s coordinate for the centerline is zero at the beginning (upstream end) of the channel and is equal to the length of the centerline at the downstream end of the channel. The s coordinate for any point is always positive."[9] Points that do not belong to the centerline have a negative n coordinate if lying to the left of the centerline or a positive n coordinate if to the right. When we plot the depth points with the new (s,n) coordinate system we obtain a stretched image with the centerline at its center (Fig. 07).
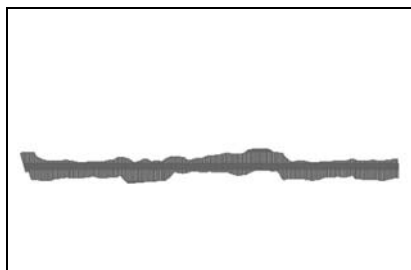

Fig. 07, FishNet on the (s,n) coordinate system

We interpolate a new DEM from this layout and apply the FishNet tool to obtain a grid of perpendicular polylines along the channel. By converting the fishnet back to (x,y) coordinates we have a set of cross sections to the original channel which we will use later on to calculate the width of the natural channel.
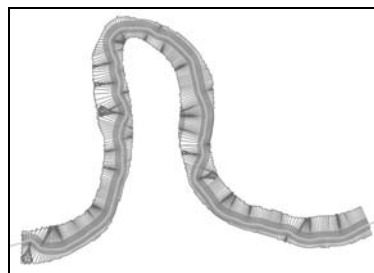

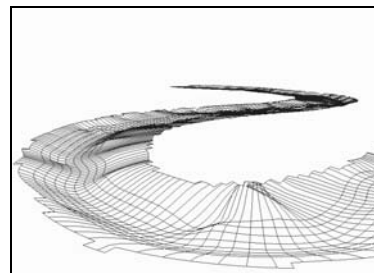Fig. 08, FishNet on the (x,y) coordinate system

Fig. 09, A 3D view of the FishNet using ArcScan

4. Ship Size Determination According to Channel Characteristics

There are two basic measures that influence the maximum ship size a river channel can accommodate. These are depth for draught and curves radii for length overall. However, in order to correctly establish a safe navigational channel, certain guidelines should be followed. In this case, we refer to the Permanent International Association of Navigation Congresses (PIANC), "Approach Channels. A Guide for Design", 1997 [4].

The San Gonzalo is a natural channel which extends for 72 km between the Merin Lagoon and the Los Patos Lagoon. Some km before the city of Pelotas, the San Gonzalo lock (Fig. 10) is located. Its main purpose is to prevent contamination of the fresh water Merin Lagoon from the salty water of the Los Patos Lagoon. The lock was built in 1975 and is administered by the Agency of the Merin Lagoon, a dependent branch of the Federal University of Pelotas.
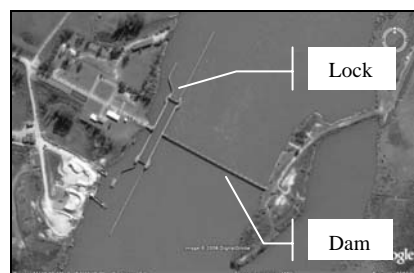

Fig. 10, Lock of the San Gonzalo channel

The lock limits the size of the ships to a maximum of 120 m LOA, 15.5 m Beam and 4 m Draught. This is the standard size of all locks connecting to the Los Patos Lagoon in Brazil.

We begin then with a maximum beam value of 15.5 m.

5. Maximum Draught Determination

The curve of water permanence for the Cebollatí River

shows a mean value of +1.45 m and a value of +1.0 m during at least 60% of the year. At the beginning of the paper we explained how we had deepened the data by 1.5 m, by taking into account the water permanence curve, we now consider the water level to be at -0.5 m of what our data shows during most of the time [1].

The minimum continuous depth determined by the contour lines is -1.50 m along the whole extension of the area studied. For the sole purpose of illustration we study the methodology for a depth of -2.0 m which appears not constant. After correcting the value of -2.0 m selected for our previous deepening, we end up with the data representing a real minimum depth of -1.5 m.

It is important to note that the maximum draught is one of the variables to take into consideration when studying the economical feasibility of the proposed ship. Our objective is to find the best trade off between ship size (i.e. capacity for cargo) and channel opening / maintenance so that the venture remains profitable. We expect the ship to keep an under the keel clearance of 0.50 m at all times which would determine its draught. The relationship depth-draught would then be:

$$h/T = 1.5/1.0 = 1.5 \tag{0.1}$$

Our maximum draught then becomes $T = 1.0$ m.

6. Maximum Speed Determination

The speed of the ship is limited by its Froude number:

$$F_{nh} = \frac{v}{\sqrt{g \cdot h}} \tag{0.2}$$

Where:
- v is the speed of the ship respect to the water in m/s
- h is the depth of the water in meters
- g is the gravity force acceleration (9.81 m/s²)

We obtain the following results for different values of h and v:

Table 03 - Froude Number Determination

		$h = 1.5$ m	$h = 2.0$ m	$h = 2.5$ m
v (kt)	v (m/s)	F_{nh}	F_{nh}	F_{nh}
3.00	1.54	0.40	0.35	0.31
4.00	2.06	0.54	0.46	0.42
5.00	2.57	0.67	0.58	0.52
6.00	3.09	0.80	0.70	0.62
7.00	3.60	0.94	0.81	0.73
8.00	4.12	1.07	0.93	0.83
9.00	4.63	1.21	1.05	0.93
10.00	5.14	1.34	1.16	1.04

As F_{nh} gets closer to unity, resistance to movement reaches very high values which most of the ships find very difficult to handle. It also shows an important increase of the squat effect or descent of the keel due to suction effects produced by water displacement. The guide for design of approach channels by the Permanent International Association of Navigation Congresses (PIANC) recommends that for cargo vessels the value of $F_{nh} = 0.7$ should not be exceeded.

For our selected depth of 1.5 m, the recommendation sets our maximum speed to be 5 *kts*.

7. Channel Width Determination

The PIANC recommendation to determine the channel width is based on the beam of the vessel. As noted before, our maximum beam is 15.5 m. On the economic feasibility study done by CSI Ingenieros S. R. L. – Serman & Asociados in Uruguay, the channel width calculated for a good maneuvering ship following the PIANC recommendations was found to be 34 m. This width is still 10% larger than the Sangradouro channel kept by the Brazilian government on the Merin Lagoon.

The over width on the curves of the channel can be calculated by using Semenov's formula:

$$B = 0.7 \frac{L^2}{R} \tag{0.3}$$

Where,
- L is the length of the model ship
- R is the radius of the curve

For the purpose of evaluating the size of the extra width with the help of ArcGIS®, we selected three different curves along the thalweg and calculated B for different lengths of ships.

Fig. 11, Curve No.1

Table 04 - Channel over width for different curve radii and LOA

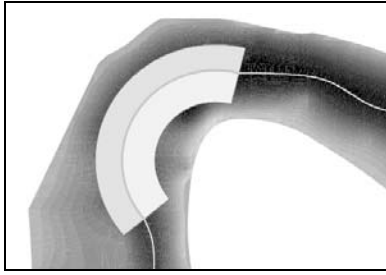|	Curve No 1	Curve No 2	Curve No 3
Radii =	119.292 m	345.132 m	496.417 m
LOA	**B1**	**B2**	**B3**
65	24.79	1.25	0.00
70	28.75	1.68	0.00
75	33.01	2.21	0.01
80	37.55	2.86	0.01
85	42.40	3.65	0.02
90	47.53	4.58	0.03
95	52.96	5.69	0.05
100	58.68	6.98	0.07

Fig. 12, Curve No.1 showing a 34 m buffer on its left side and an extra 42 m buffer –corresponding to a ship beam of 85 m- to the right of it.

8. Dredging Volume and LOA Determination

With the information about the width of the channel, we can use ArcGIS to help us draw the channel and then calculate the volume that may be necessary to dredge.

The procedure to achieve that was as follows:

1. Extract the contour line of depth -2.0 m from the contour feature class
2. Create a polygon feature class from the contour line
3. Clip the cross sections obtained in section 5 with the contour polygon
4. Locate the midpoints of the cropped cross section and unite them into a new center line
5. Create a new feature class with geometrical curves that best approximate the center line
6. Calculate the radii of the curves and create new fields on the attributes table to store the value of the Semenov's formula for different lengths
7. Create a buffer of the line with the values of the Semenov's formula plus the width of 34 m
8. Intersect the obtained buffer with the previously generated TIN of the river section
9. Calculate the volume enclosed within the space defined by the area of the buffer and the -2.0 m depth plane

The results that we obtained for the different lengths of ships for a depth of 1.5 m are shown in Table 05.

Table 05 – Dredging volumes for different values of LOA

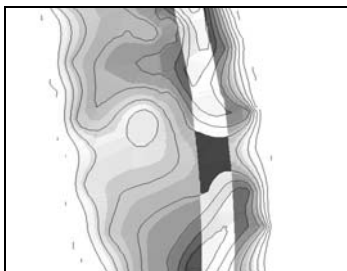| LOA (m)	2D Area	Surface Area	Volume (m³)	Estimated cost (1.4 USD per m³)
80	3557.96	3562.05	626.61	877
85	3794.71	3799.45	704.39	986
90	4056.68	4062.14	803.84	1125
95	4351.51	4357.72	918.55	1286
100	4681.94	4688.99	1059.42	1483

Fig. 13, Area to be dredged (in black) for a LOA value of 80 m

The Squat effect can be calculated by applying the equation:

$$Squat\ (m) = 2.4 \frac{D}{L_{pp}^{2}} \frac{F_{nh}^{2}}{\sqrt{\left(1 - F_{nh}^{2}\right)}} \qquad (0.4)$$

With,

$$D = B_C \cdot L_{pp} \cdot B \cdot T \qquad (0.5)$$

Where:

- D being the displacement volume of the vessel in m³
- L_{pp} is the length between perpendiculars of the vessel
- B is the beam of the vessel
- T is the draught in m
- B_C is the block coefficient of the vessel

We then calculate the squat effect for the following parameters,

- Beam: 15.5 m
- Depth: 1.5 m
- Draught: 1.0 m
- Max. speed in the channel: 5 kts
- LOA: 80.0 m ~ 100.0 m
- L_{pp}: 0.50 m ~ 2.0 m shorter than LOA
- B_C: 0.90 ~ 0.70

Table 06 – Extract of the squat effect calculation for a 80 m LOA

F_{nh}	Beam (m)	Draught (m)	LOA (m)	L_{pp} (m)	B_c	D (m³)	Squat (m)
0.67	15.50	1.00	80.00	79.50	0.90	1109.03	0.25
					0.85	1047.41	0.24
					0.80	985.80	0.23
					0.75	924.19	0.21
					0.70	862.58	0.20
				79.00	0.90	1102.05	0.26
					0.85	1040.83	0.24
					0.80	979.60	0.23
					0.75	918.38	0.21
					0.70	857.15	0.20
				78.50	0.90	1095.08	0.26
					0.85	1034.24	0.24
					0.80	973.40	0.23
					0.75	912.56	0.21
					0.70	851.73	0.20
				78.00	0.90	1088.10	0.26
					0.85	1027.65	0.25
					0.80	967.20	0.23
					0.75	906.75	0.22
					0.70	846.30	0.20

The results show that for every configuration, the squat varies less than 0.10 m and it never goes beyond 0.26 m.

Conclusions

Using a GIS to model and study a river for navigation prospects is an important step forward in order to achieve a better understanding of the river-vessel system. The non invasive approach a digital assessment provides is very valuable at the time of making planning decisions. The GIS allow us to rapidly change parameters and see results in real time; as well as giving us the opportunity to better improve the system by the inclusion of new developed data as soon as it becomes available.

The methodology presented on this paper is still a work in

progress. There are many tasks the authors would like to see in the direction of more automatized and optimized processes. However, this brief example shows how far it is possible to get from a modest set of data. Once a suitable range of model data is collected, a search for a real world match can be conducted and/or designs for a new ship developed.

In this example we found out that it is possible to navigate the river on a ship with the following characteristics:

- Beam: 15.5 m
- LOA: up to 100 m
- Draught: 1.0 m
- Speed: 5 kts

It is difficult to imagine such a ship and even more difficult to imagine it carrying any substantial amount of cargo. However, the cost for dredging a channel capable of accommodating such a ship in the area studied is only (estimated) 1483 USD.

The immediate next step is to extend the methodology to the whole of the river and take full economical considerations into account.

Because of lack of proper data, the extension of the river floodplain was not considered for this paper.

References

1. CC. (CG) (R) Juan José Mazzeo, "*Hidrovía del Este*", April 2001.

2. Compañía Fluvial y Lacustre Oriental, "*Proyecto Terminal de Cargas La Charqueada*", Cargo terminal project proposal, June 2002.

3. Consorcio Oriental, CSI Ingenieros S. R. L. – Serman & Asociados, "*Estudio de Factibilidad y Análisis de Alternativas para el Transporte Multimodal en la Región Litoral Este y en Particular el Transporte del Arroz.*", Economic feasibility study, 2002.

4. "Approach Channels. A Guide for Design", PIANC, Final Report of the Joint Working Group PIANC, and IAPH, in cooperation with IMPA and IALA, Supplement to Bulletin No. 95, 1997.

5. José Luiz Fay de Azambuja, "*Hidrovia da Lagoa Mirim: Um Marco de Desenvolvimento nos Caminhos do MERCOSUL*" Master Thesis, School of Engineering - Federal University of Rio Grande do Sul, Porto Alegre 2004.

6. Estudio Ingeniería Ambiental, Timonsur S. A. "*Terminal de Carga La Charqueada*", Environmental Impact Study, March 2003.

7. "*ArcGIS®, The Complete Geographic Information System*", ESRI 2005.

8. David R. Maidment, "*Arc Hydro, GIS for Water Resources*", ESRI Press 2002.

9. Venkatesh M. Merwade, David R. Maidment and Ben R. Hodges, "*Geospatial representation of river channels*", Center for Research in Water Resources - University of Texas at Austin, 2003.