Proceedings of the *FOSS/GRASS Users Conference 2004* - Bangkok, Thailand, 12-14 September 2004

DTM of a braided river: how to reproduce it?

Bianca Federici*, Domenico Sguerso**

* DIAM - Department of environmental engineering - University of Genova, Via Montallegro 1, 16149
Genova, Italy, email: obelix@diam.unige.it

** DIMSET - Department of fluid machinery, power plants and transportation - University of Genova,
email: domenico.sguerso@unige.it

1 Introduction

The main goal of several researches is monitoring the territory, with different survey techniques and analysis methods. Many survey methodologies may be applied to study 3Dimensional variation; generally the choice depends on the application for which the survey is asked, the size of the area, the accuracy and so on. Frequently a quick and economical approach should represents an useful strategy to gain land metric knowledge. Moreover, the knowledge of the territory depends on the application that needs it.

A typical application is braided river analysis. The main features of a braided river is the existence of more than one channel contributing to flow and sediment transport (fig. 1). Such channels, separated by deposition areas called bars, are in continuous motion due to bed and bank scour during floods of even moderate intensity. So, it's possible to observe abandonment or merging of old channels, creation of new channel, or simply shifting of channels in the floodplain. Due to the rapid and strong changes in stream patterns, braided rivers pose difficult problems of river regulation and management. To investigate the processes that control the morphodynamics of braided networks, fluvial geomorphologists and engineers preliminary need a detailed survey.

Aerial photogrammetry, laser altimetry and satellite high resolution images processing are recently used to produce Digital Terrain Models of wide braided river at a high spatial (1x1 m point spacing or less) and temporal (event-based) resolution. However, such survey methods are useful primarily for the dry portion of the floodplain; thus, when we have to deal with submerged zones, or when the dimensions of the area are not wide enough, a ground survey has to be used to fill in such areas.

To reproduce the main shapes and features of a braided river, i.e. the position and entity of deposition and erosion zones, detailed ground surveys are usually performed. Obviously a complete and onerous field data collections is needed, but economize the costs of the survey increase the frequency monitoring; in this way it is possible to gain a better description of the morphology's evolution.

In the present work we investigate how optimize the topographic survey, in the sense of reducing the number of topographic points that we have to survey, understanding which kind of topographic data are needed to better reproduce such complex surface.

Tests are based on different synthetic Digital Terrain Model (DTM), principally representing a schematic braided river and its characteristics (section 2.1). Exporting transversal cross-sections and/or break-lines from such surface, we test different interpolating methods presented in the open source and free software Geographical Information System (GIS) GRASS 5.3, in different survey simulations (sections 2.3 and 2.4). Note that a crucial feature of the surface that we try to reproduce, is its strong anisotropy in different directions, due to the presence of different but important directions of the water flowing on such surface.

A comparison is needed with a software used in the hydraulic engineering practice, HEC-RAS software, starting from significant transversal sections of the synthetic DTM (section 2.5).

Comparing the interpolating methods with different kind of data, quantity and their spatial distribution, we point out few and very simple suggestions.

Figure 1: View of a short reach of a braided river: the Borbera River (Italy). [Water flows from left to right]

2 How to reproduce a braided river DTM?

The main goal of the present work is to optimize a topographic survey in the sense of how many points and which distribution is necessary for a good representation of the morphology of a particular geometry: the braided river.

In other words, the question is: is it better to survey points on a regular grid, transversal cross sections, longitudinal profiles of the main channels and/or break-lines (lines of strong slope changes, i.e. well-defined channel banks)? And which spatial density is needed? The answer obviously depends on the 3D geometry of the territory (morphology), but also on which particular characteristics of the territory we want to represents that directly depends on the application for which the Digital Terrain Model (DTM) will use. It's also important to understand if, in the specific application, is more important to reproduce the shape of the territory with a dense data set or observe few points in strategic area. Last but not least, the answer to the previous questions depend on the interpolating method used to create the DTM.

A DTM is a mathematical instruments that allow to represent numerically every surface. The terrain representation of a surface may be done by different data set: contour lines, sparse elevation points or raster file characterized by an elevation associated at every pixel. Note that, a discretization is always present even if the point/pixel density is high. Hence, when we have to investigate the surface model on different points or with different spacing, we have to carry out elevations data through mathematical estimate algorithms.

The interpolating algorithms may be based on deterministic or stochastic models. In a deterministic model, the relation between two near points is expressed by an explicit law; instead, in a stochastic model the influence of different points is expressed by a statistic parameter (covariance). Moreover, an interpolator may be global or local if all the data or only the nearest data, respectively, are used to create the model. The global methods are useful to individuate the general data trend; instead, the local methods usually follow better the undulations of the surface.

In GRASS 5.3 the Inverse Distance Squared Weighting (IDW) and Regularized Spline with Tension (RST) are available [5,6]; moreover kriging method may be used too, interfacing GRASS with the R geostatistical software.

Kriging is a geostatistical interpolation method that has proven useful and popular in many fields, especially in case of irregularly spaced data. An important component of the kriging method is the variogram; it's estimation is the crucial point of the procedure. This method is very important, so we cannot neglect to interpolate observed data with it but, for the same reason, it is necessary to test the kriging with an appropriate analysis.

Thus, by now, we will focused our attention on inverse distance weight and spline. In the near future we will analyse kriging too.

In general none interpolator is better than the others, but it depends on the observed data and on the shape to reproduce. Moreover, the quality of the interpolation also depends on the user's experience; in fact the parameter's setting may be very important when surface and data set are not optimal: rough surface and sparse data.

2.1 Synthetic DTM

We investigated and studied a procedure starting from two synthetic DTMs representative of a floodplain, characterized by constant slope, in which the following rivers are cut respectively:
- a simple braided river with trapezoidal cross-section (fig. 2),
- a straight single-channel river with semicircular cross-section (fig. 3).

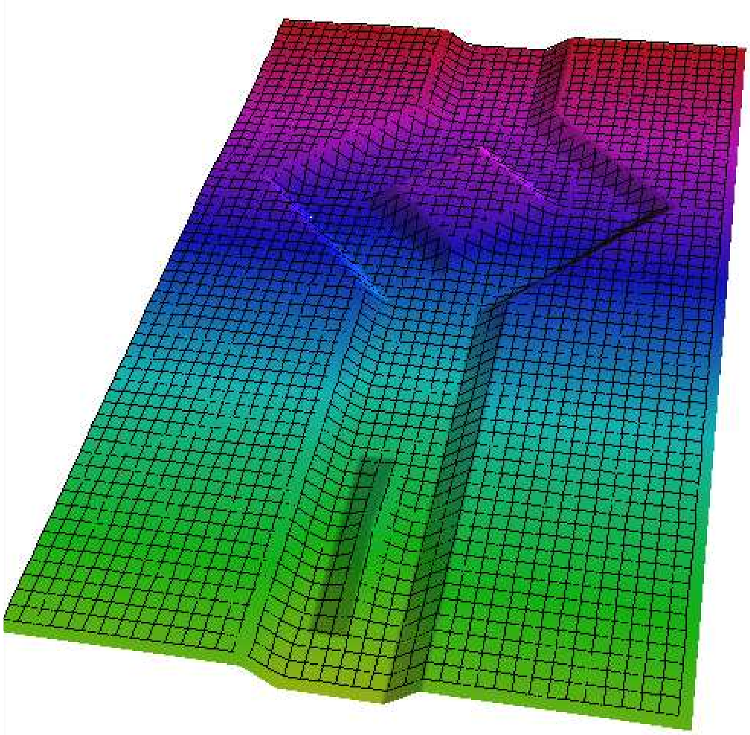

Figure 2: 3D view of the synthetic braided river DTM. [Water flows from up to down]

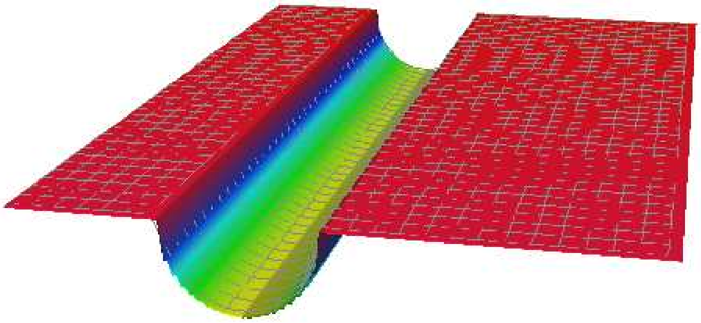

Figure 3: 3D view of the synthetic DTM representing a straight single-channel river with semicircular cross-section. [Water flows from up to down]

A synthetic DTM has the advantage to be characterized by a geometry simpler than in nature, but, at the same time, reproduces some important features of a real morphology. Hence, the first DTM reproduces schematically three main features of a braided river: a bifurcation of one channel in two, a confluence of two channel in one, and the presence of a deposition zone, called bar, inside a channel (in the straight downstream channel in our DTM); in the second DTM we wanted to reproduce the fact that the bed of a natural river is usually not flat, and that the bank toe, the point that identify the end of the channel bank and the beginning of the channel bed (that in the following we call "wet break-line"), is often not easy to identify.

During our analysis, such synthetic surfaces represent the reality.

A crucial feature of all the two synthetic surfaces that poses problems from the interpolating point of view, is their strong anisotropy, due to the presence of a main floodplain slope and so of a main direction of the water flowing on such surface. Many interpolators are able to take into account anisotropy, but usually anisotropy has to be uniform over the whole interpolation area. Hence, when you have to reproduce a braided river, where every channel moves in different directions, you are not able to set an anisotropy parameter because it is impossible to identify a unique anisotropy direction.

More difficulties arise when you have to reproduce a braided river, due to the fact that:
- their dimensions are not very sizeable, i.e. channel depth may be just 1 m and channel width may be 10 m or less,
- the width to depth ratio is an important parameter for their morphodynamic evolution, hence it has to be reproduced carefully,
- usually every channel is characterized by a different average bed slope.

Moreover, in the specific application of braided river, it's more important to reproduce the shape of the surface than the accuracy of the interpolated DTM. In fact, the surveyed data may have an error equal to the average grain size of the sediments, that for a braided river like the Borbera River (fig. 1) is of the order of 10 cm, i.e. 10% of the channel depth. Hence, the accepted interpolation error could be of such order.

2.2 Procedure in GRASS and error evaluation

The input data consist in a synthetic DTM as described in sect. 2.1. The synthetic DTM was created by a spreadsheet giving a value of elevation to every cell. In this way we created a matrix of values we could import in GRASS as a raster file by the command *r.in.ascii*. Then, because we needed the 3Dimensional coordinates of every pixel in a file, we transformed the raster map into a sites map by *r.to.sites*.

To simulate the data survey, we extracted from such sites file the points corresponding to cross-sections and/or break-lines, transforming the GRASS sites file in an ascii one by *s.out.ascii* and then using a proper FORTRAN program to extract the series of points we need. With this procedure we obtained the observed data of a real survey that we imported in GRASS by *s.in.ascii*, and began to elaborate.

We tried to re-create the original synthetic surface through a spatial interpolation. GRASS 5.3 offers two interpolation techniques: Inverse Distance squared Weighting (IDW) with the command *s.surf.idw* and Regularized Spline with Tension (RST) with the command *s.surf.rst*. We tested both of them and optimized the parameters in function of the input data, estimating the differences between the original surface and the interpolated ones.

Sometimes the good quality of an interpolation, if evident, can be evaluated through a qualitatively comparison between the reference surface and the interpolated one. Anyway, the error is usually quantified by means of numerical comparison of every pixel of the interpolated surface with the corresponding pixel of the reference one. However, when the reference surface is close to be vertical and the interpolated surface reproduce well the behavior but, for example, it is slightly shifted planimetrically, the error evaluated through a simple vertical difference of every pixel is not representative of the interpolation quality (fig. 4). For this reason, the minimum distance from every pixel of the interpolated surface to the reference surface has to be calculated.

We performed this calculation in GRASS using *r.mapcalc*, a very useful command that permits to create new raster map by applying mathematical operations to one or more existing raster maps. We create a new raster map, the error map, assigning to a pixel the value corresponding to the minimum distance between the pixel value of the interpolated raster and the values of 25 pixels of the reference raster around the resulting cell. Error is positive if the reference value is higher than the interpolated one, and vice versa. Obviously, the amplitude of the area at which you have to apply the minimum distance research depends on the surface shape.

In the next section we try to test the interpolation methods implemented in Grass, inverse distance weight and spline, with different synthetic DTMs and different data sets. We try to understand which criteria we have to follow to select interpolation method and setting parameters value, in order to obtain a good interpretation of real surface.

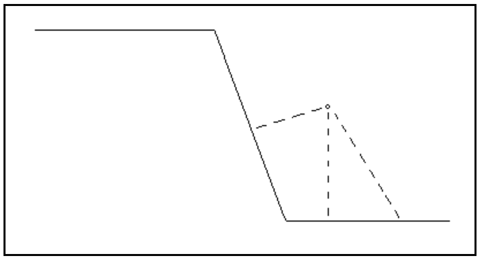

Figure 4: Sketch showing the difference between errors estimated by calculating vertical distance or by searching minimum distance.

2.3 Inverse Distance Weighting

The Inverse Distance Weighting (IDW) method is a weighted average interpolator. Data are weighted during interpolation such that the influence of one point relative to another declines with distance between them. The weights assigned to the data points are fractions, and the sum of all the weights is equal to 1.0.

Weighting is assigned to data using a weighting power that controls how the weighting factors drop off as distance from a grid node increases. The greater the weighting power, the less effect points far from the grid node have during interpolation. As the power increases, the grid node value approaches the value of the nearest point. For a smaller power, the weights are more evenly distributed among the neighboring data points.

The equation used for Inverse Distance to a Power is:

$$z_j = \frac{\sum_{i=1}^{n} z_i / d_{ij}^{\beta}}{\sum_{i=1}^{n} 1/d_{ij}^{\beta}}, \tag{1}$$

where:
z_j is the interpolated value for grid node j,
z_i are the neighboring points,
d_{ij} is the distance between the grid node j and the neighboring point i,
n is the number of points to use for the interpolation,
β is the weighting power.
The resulting surface depends on the weighting power and on the parameter n.

IDW is one of the simplest and most readily available method. Moreover, it is very fast. It has also the advantage to restrict the spatial influence of any errors, but it has the disadvantage to generate “bull’s eyes” patterns of concentric contours around the surveyed data. Furthermore, this model doesn’t take into account a possible anisotropy of the surface.

2.3.1 Application of IDW in GRASS

In GRASS 5.3 the command to perform surface interpolation from sites data by Inverse Distance Weighting is *s.surf.idw* [5,6].
This program allows the user to use a GRASS site list file as input, and create a raster file as output.
The weighting power is fixed, equal to 2.
The parameter that the user can modify is *npoints*, i.e. the number of points to use for interpolation. Its default value is 12, and it’s not possible to set a value greater than the default one.

2.3.2 Application on synthetic braided river DTM

We analysed IDW interpolation starting from the synthetic braided river DTM, keeping the default value of the parameter *npoints*.

Because river topographic data usually surveyed are transversal cross-sections, we imported sites relative to different transversal cross-sections and interpolated them.

In the first survey that we performed, the distance between two ’surveyed’ cross-sections was 6 m (= 20 pixels) while the distance between two following points in a cross-section was 0.3 m (= 1 pixel).

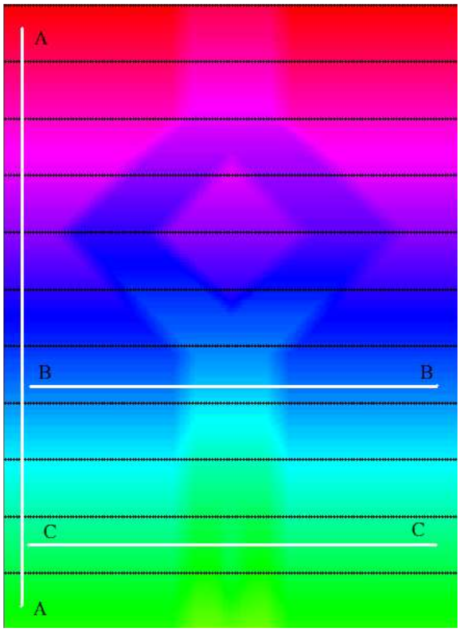

Figure 5: Position of the 'surveyed' cross-sections [black lines] and of three significant sections [white lines] on the synthetic braided river DTM. The distance between two 'surveyed' cross-section is 6 m (= 20 pixels) while the distance between two following points in a cross-section is 0.3 m (= 1 pixel).

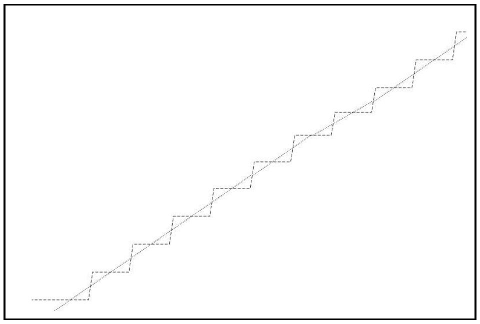

Figure 6: Comparison between interpolated and reference values along the longitudinal section (A-A) on the floodplain of the synthetic braided river DTM with IDW. [The distance between two 'surveyed' sections is 6 m (= 20 pixels) while the distance between two following points in a cross-section is 0.3 m (= 1 pixel).]

To analyse the outcome DTM, we extracted three sections as indicated in figure 5: the longitudinal section (A-A) on the floodplain, the transversal section (B-B) in correspondence of the straight downstream reach, and the transversal section (C-C) in correspondence of the central bar in the straight downstream reach. And we compared the interpolated values with the synthetic ones.

If you look at figure 6 you may notice that the constant slope plane was reproduced as a sequence of steps, i.e. area of constant elevation from the transversal wheelbase of one section (k) and the previous one (k-1) to the transversal wheelbase of such section (k) and the following one (k+1). It happens because the elevation of a pixel located between the section k and the transversal wheelbase of the sections k and k+1, for example, depends only on the elevation of the closest 12 sites that all belong to the section k. If you look at figures 7 and 8, you may notice that the shape of the sections in the straight reach was quite well reproduced but moved all up or down depending on the position of the interpolated section related to the section data. This behavior is due to the excessive data anisotropy, too dense in the transversal direction.

To overcome this problem we tried to survey less points along one cross-section. Hence, in this second survey the distance between two 'surveyed' sections was always 6 m (= 20 pixels) while the distance between two following points in a cross-section was 1.5 m (= 5 pixels).

In figure 9 is reported the longitudinal section (A-A) relative to this case compared with the correspond-

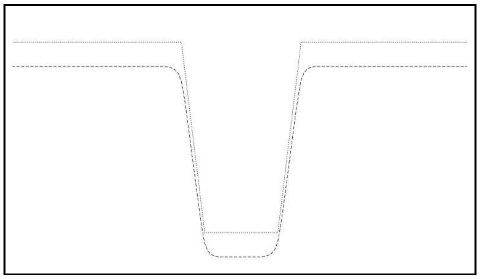

Figure 7: Comparison between interpolated and reference values along the transversal section (B-B) in the straight downstream reach of the synthetic braided river DTM with IDW. [The distance between two ’surveyed’ sections is 6 m (= 20 pixels) while the distance between two following points in a cross-section is 0.3 m (= 1 pixel).]

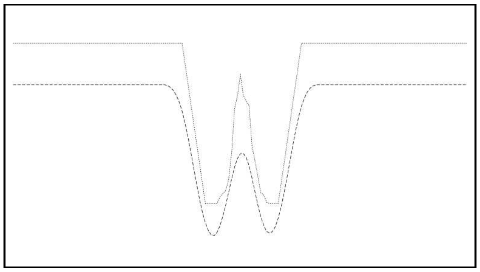

Figure 8: Comparison between interpolated and reference values along the transversal section (C-C) in the straight downstream reach in correspondence of the central bar with IDW. [The distance between two ’surveyed’ sections is 6 m (= 20 pixels) while the distance between two following points in a cross-section is 0.3 m (= 1 pixel).]

ing synthetic data. Note that the interpolation gave better results compared to figure 6. However, if you look at figures 10 and 11 an overall vertical translation of interpolated cross-sections persists.

In figure 12 is reported the error distribution relative to the DTM interpolated from this last survey. On the floodplain the error oscillates between +0.22 m and -0.22 m, while in the channel the average is about -0.3 m but it may reach 0.6-0.8 m (60%-80% channel depth) close to the banks or in correspondence of the central bar, i.e. where the topography changes more rapidly.

It seems that IDW should work better if data points are deprived of their trend, that in our application corresponds to the mean slope of the floodplain. But it is not easy in a natural braided river because every channel is characterized by its own slope.

Then, we performed a third survey, taking data on a regular grid 6 m x 6 m (= 20x20 pixels). The error distribution (fig. 13) is worse almost everywhere in the channels (> 0.6 m, i.e. 60% channel depth) except for circular area around the data sites, what it’s called the “bull’s eyes” pattern, typical of IDW.

Instead, if the ’surveyed’ data are on a dense regular grid with spacing 0.9 m x 0.9 m (= 3x3 pixels), the error distribution is optimal, mostly lower than 0.03 m (3% channel depth), of the order of 0.25 m (25% channel depth) in correspondence of slope changes, and with some localized peaks or craters (fig. 14).

Summarizing, IDW interpolator needs a huge amount of data, on a regular grid if possible, also to reproduce a regular straight channel; and this is not a realistic condition if you want to survey a reach of a braided river with ground techniques. We confirmed what suggested by Neteler & Mitasova (2002), p. 166: IDW is useful when the data density is higher than the density of the resulting grid points.

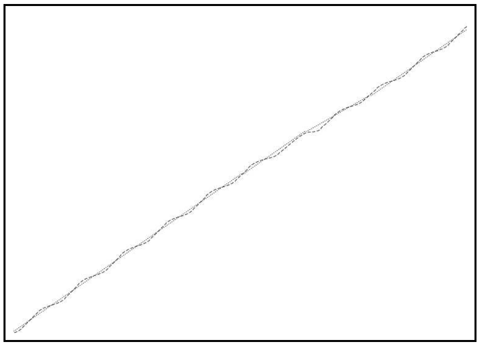

Figure 9: Comparison between interpolated and reference values along the longitudinal section (A-A) on the floodplain with IDW. [The distance between two ’surveyed’ sections is 6 m (= 20 pixels) while the distance between two following points in a cross-section is 1.5 m (= 5 pixels).]

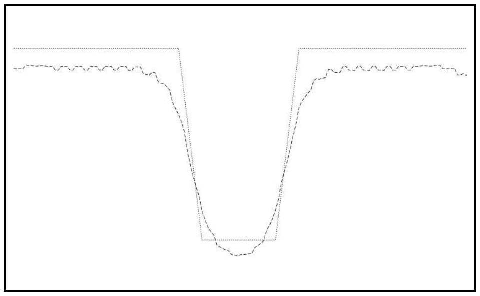

Figure 10: Comparison between interpolated and reference values along the transversal section (B-B) of the straight reach with IDW. [The distance between two ’surveyed’ sections is 6 m (= 20 pixels) while the distance between two following points in a cross-section is 1.5 m (= 5 pixels).]

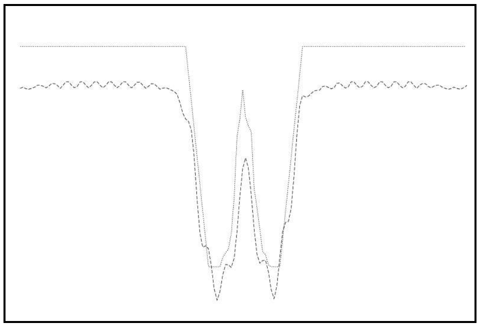

Figure 11: Comparison between interpolated and reference values along the transversal section (C-C) of the straight reach in correspondence of the central bar with IDW. [The distance between two ’surveyed’ sections is 6 m (= 20 pixels) while the distance between two following points in a cross-section is 1.5 m (= 5 pixels).]

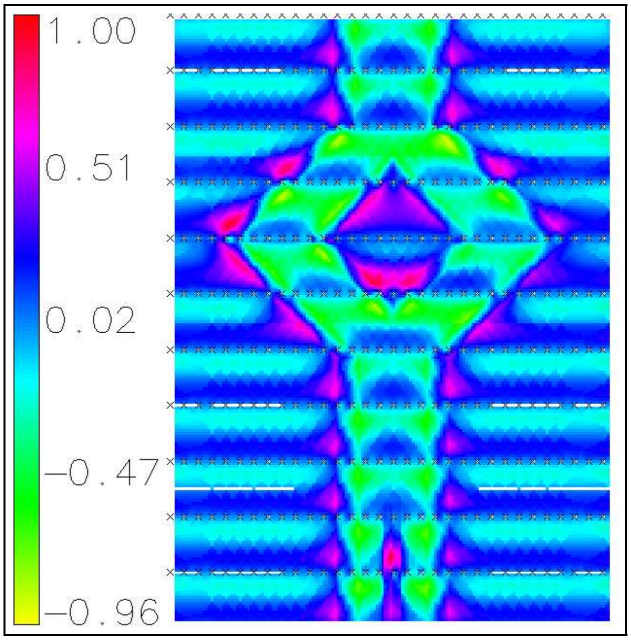

Figure 12: Error distribution [m] of DTM interpolated with IDW from sites, when the distance between two 'surveyed' sections is 6 m (= 20 pixels) while the distance between two following points in a cross-section is 1.5 m (= 5 pixels). [Crosses indicates the 'surveyed' points.]

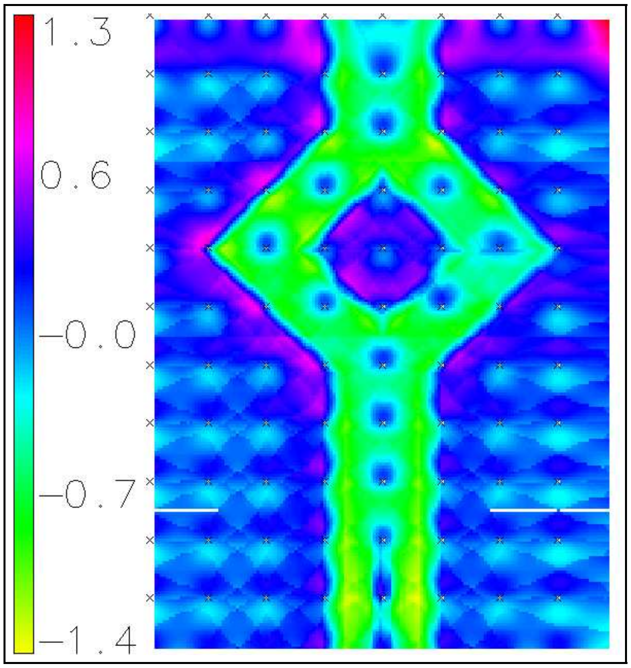

Figure 13: Error distribution [m] of DTM interpolated with IDW from sites, when both the distance between two 'surveyed' sections and the distance between two following points in a cross-section is 6 m (= 20 pixels). [Crosses indicates the 'surveyed' points.]

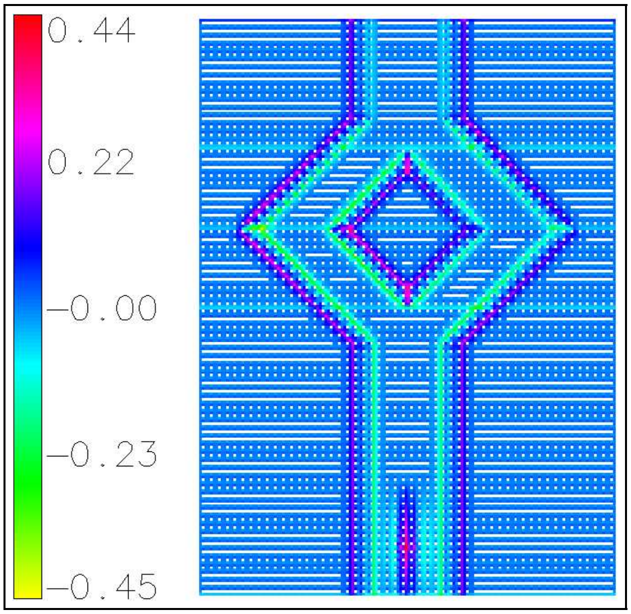

Figure 14: Error distribution [m] of DTM interpolated with IDW from sites, when both the distance between two 'surveyed' sections and the distance between two following points in a cross-section is 0.9 m (= 3 pixels).

2.4 Spline

A spline is a smooth curve defined mathematically by two or more points called knots. The term comes from the spline gadget used by shipbuilders to draw smooth shapes. A spline takes the shape which minimizes the energy required for bending it between the fixed points, and thus adopt the smoothest possible shape.

The important characteristic of spline functions is that they are piecewise polynomial function: different polynomials may be used in different parts of a curve. A significant advantage of this approach is that it can follow a large, complex curve by using low degree polynomials.

Different types of spline exist, depending on the polynomial degree [1,2]. A function S is called a spline of degree k if:

1. The domain of S is an interval $[a,b]$
2. $S, S', ..., S^{(k-1)}$ are all continuous functions on [a, b]
3. There are knots t_i such that $a = t_0 < t_1 < ...$ and such that S is a polynomial of degree at most k on each subinterval $[t_i, t_{i+1}]$.

The assumption that the interpolation function should be as smooth as possible is mathematically expressed by the condition that the sum of the deviations from the measured points and the smoothness seminorm of the spline function $F(\mathbf{r})$ has to be minimum:

$$\sum_{i=1}^{n} |z_i - F(\mathbf{r}_i)|^2 w_i + w_0 ||F||^2 = minimum, \tag{2}$$

where:
z_i is the interpolated value for grid node i,
$\mathbf{r}_i$ is the discrete point where the phenomenon is measured,
w_i, w_0 are positive weights,
$||F||$ is the seminorm of the spline function, and it may assume different expression [1,2,3].

The simplicity of representation and the ease with which a complex spline's shape may be computed make spline a popular representation for curves in computer science, predominantly in computer graphics but also for other kinds of interpolations.

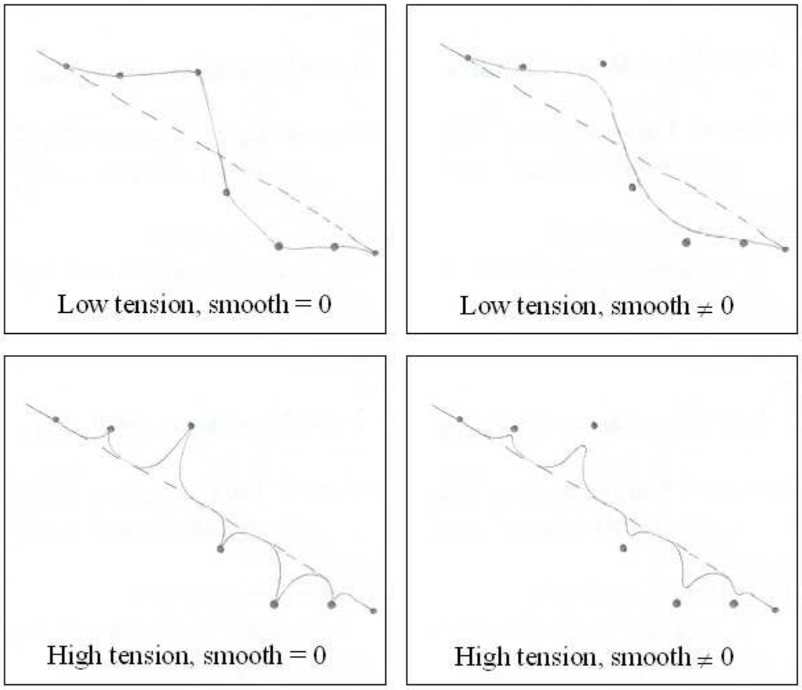

Figure 15: Sketch of RST interpolation results with high/low tension and smoothing equal or not to zero. [The dotted line represents the data trend.]

2.4.1 Application of Spline in GRASS

In GRASS the regularized spline with tension (RST) method is used [3,4]. The RST function includes the sum of all derivatives up to infinity with rapidly decreasing weights, so that the resulting surface has regular derivatives of all order. Moreover, a tension parameter appears, hence the surface can be tuned from an "elastic membrane" to a "thin steel plate".

The command to perform surface interpolation from sites by regularized spline with tension is $s.surf.rst$. User can define many parameters, the principal ones are: $tension$, $smoothing$, $npmin$, $segmax$, $theta$ and $scalex$. In the following, we will underline some characteristics of such parameters [5,6].

Smoothing allows the surface to deviate from the data points in its effort to minimize its energy. Instead, the interpolation function passes exactly through the observed data if smoothing is set to zero.
The default smoothing value is equal to 0.1, hence an approximation is allowed. Note that smoothing may be useful for removing the noise which may be present in observed data.
In our applications we always imposed smoothing equal to zero, assuming that the values of data points are exact.

Tension parameter, as already said, tunes the surface from an "elastic membrane" to a "thin steel plate". High tension "increases the distances" between points, so reduces the range of impact of each point. Surface with too high tension (for example =160) behaves like a membrane with peak or pit in each given point and everywhere else the surface goes rapidly to trend. Low tension "decreases the distances" between points, hence the points influence each other over longer range. Surface with too low tension (for example =10) behaves like a stiff plate hard to bend, hence a very smooth surface.
The default tension value is equal to 40, but such value has to be modified depending on the shape of the surface you want to describe.
A sketch explaining the different behavior of tension and smoothing parameters is reported in figure 15.

For processing of large data sets, which are common in geosciences, a segmentation algorithm with flexible size of overlapping neighborhood is available. The idea of segmentation processing is based on the fact that, for large data set, the behavior of the interpolation function is local: this means that the interpolation function in some limited area is not sensitive to data at some sufficiently distant point. Moreover, segmen-

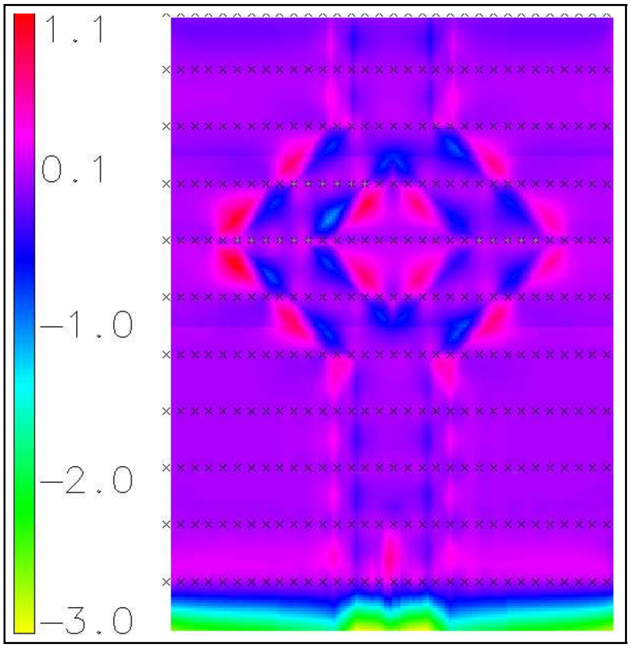

Figure 16: Error distribution [m] of DTM of the synthetic braided river interpolating with RST from sites, when the distance between two 'surveyed' sections is 6 m (= 20 pixels) while the distance between two following points in a cross-section is 1.5 m (= 5 pixels). [Crosses indicates the 'surveyed' points.]

tation limits computational demands. Hence, the interpolated area may be divided into a regular mesh of rectangular segments [4,5,6] with size dependent on the density of data points and defined by the parameter **segmax**. In particular, segmax defines the maximum number of points per segment, so segmentation processing is activated only if the number of given points is larger than segmax. Interpolation is performed on each segment of the region, using the same function for all grid points within a segment. This fact implies that each segment has to include uniform data, hence segmax depends on the surface to reproduce and on data density. In section 2.4.2 the effect of wrong setting of segmax is showed.

To ensure the smooth connection of segments, values of the interpolation function in a given segment are computed using the points from this segment and from the neighboring ones. The number of points taken for interpolation is controlled by the parameter **npmin**, the value of which must be obviously larger than segmax. Npmin is a crucial parameter in order to obtain interpolated surface of good quality. In fact, npmin must be large enough to let representing the surface trend, but not too large in order not to lose the local character typical of spline.
The default value of segmax and npmin are respectively 40 and 300.

RST method is also able to take into account anisotropy with the parameters **theta** and **scalex**, the anisotropy angle and the anisotropy scaling factor respectively. Anyway, in a braided river you are not able to identify an unique anisotropic direction, hence no anisotropic parameters have to be set (theta=0 and scalex=1).

2.4.2 Application on synthetic braided river DTM

We began looking at the behavior of RST in comparison with IDW interpolating between transversal cross-sections distant each other 6 m (= 20 pixels), with points in a cross-section distant 1.5 m (= 5 pixels), as we have already done using IDW interpolator (see fig. 12). The calculation was performed with default values of tension, segmax and npmin, and no anisotropic factors.

The errors (fig. 16) varies from 1.1 m to approximately -1 m, except for the downstream boundary zone where the error reaches -3 m. In the straight channel the interpolation works pretty well: the error is lower than 5 cm (5% channel depth) with peaks of about 30 cm (30% channel depth) along the break-lines. Instead, in the reach from the bifurcation to the confluence the errors along the break-lines are more high, up to 1 m (100% channel depth), and influence a wider area, so that the channel width is bad reproduced.

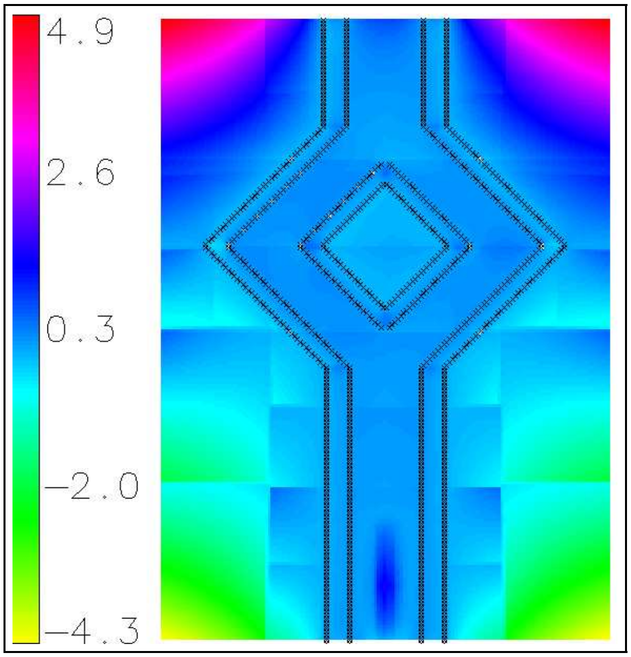

Figure 17: Error distribution [m] of DTM of the synthetic braided river interpolating with RST from data points along the breaklines, only. [Crosses indicates the ’surveyed’ points.]

However, comparing figure 16 with figure 12, we may state that RST method works better than IDW method in the application we are dealing with and surveying sites along cross-sections not too dense.

We then investigated a different approach of data survey, taking the dry and wet break-lines, i.e. the lines that identify the transversal slope change between floodplain and the channel bank, and between the channel bank and the channel bed, respectively. Break-lines are composed by 1 point every pixel along the line. The interpolation was performed with higher values of tension (=100), default values of segmax and npmin, and no anisotropic factors. Increasing tension parameter is useful in this specific calculation because the channel bed is flat and so the interpolated surface, tightened between the two wet break-lines, has a better behavior.

In figure 17 the error distribution is reported. Note boundary effects in the four corners of the region, and how the segmentation is visible. A 3D view of error distribution in which segmentation effects are evident (without boundary effects, because relative to an interpolation we will discuss in the following) is reported in figure 18. We tried to modify the segmax value so to reduce the segmentation effect: we increased it until a number greater than the data number so that the interpolator calculates one function for the whole region, and then we decreased it until 1 so that the interpolator calculates one function for every pixel, but inside the channel both the solutions were worse than the one with default value. If default values were assumed, in the straight channel the error is lower than 7 cm (7% channel depth), and in the bifurcation-confluence reach it is lower than 16 cm (16% channel depth).

It seems that the river geometry is better reproduced interpolating from data along dry and wet break-lines than along cross-sections in this particular application where the bed channel topography is flat. Note that surveying only break-lines is faster than surveying dense cross-sections. However, in a real application where bed topography is irregular, some cross-sections are needed in any case.

To remove boundary effects, we added data points along the region boundaries and the result improved as in figure 19. Errors are lower than 20 cm (20% channel depth) everywhere (< 5 cm on the floodplain and < 12 cm in the channel), except for localized peaks of about 40 cm (40% channel depth) between the dry and wet break-lines in the sharp change of direction of the channels, and for the central bar area where no observed data exist. The RST parameters were the same than in the previous interpolation. In figure 20 you may note the good comparison between the error distribution along an interpolated transversal cross-section in the straight downstream reach and the corresponding synthetic data.

We then investigated the possibility to survey the only dry break-lines plus some transversal cross-sections to have informations on the channel shape. In fact, the wet break-lines are difficult to survey in field, because not always clearly defined.

Figure 21 shows the error distribution interpolating from data points along the dry break-lines and cross-sections every 6 m (= 20 pixels), with points on a section every 1.5 m (= 5 pixels). The result is not satisfactory at all inside the channels, with errors up to 20 cm (20% channel depth) in the straight channel, up to 40 cm (40% channel depth) along the straight channel banks, and also greater than 1 m (100% channel depth) in the bifurcation-confluence reach. Instead, the floodplain is well reproduced.

It seems that a good interpolated surface can be obtained surveying both wet and dry break-lines and some cross-sections, at least in correspondence of longitudinal slope changes, where same high localized errors arise (fig. 22).

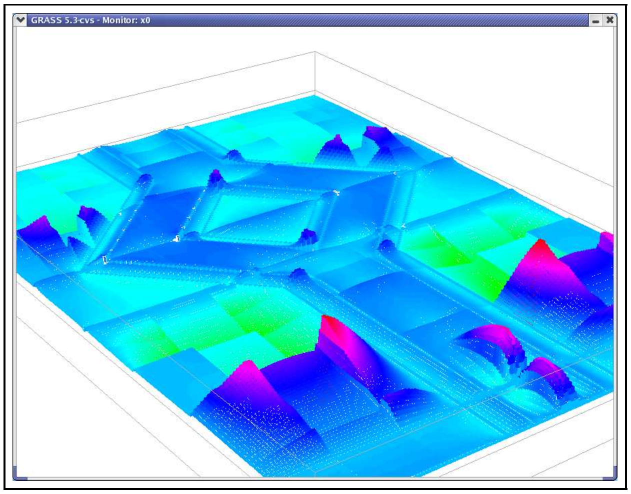

Figure 18: 3D view of the error distribution interpolating with RST from data points along breaklines, region boundary and some cross-sections. Segmentation effects are evident.

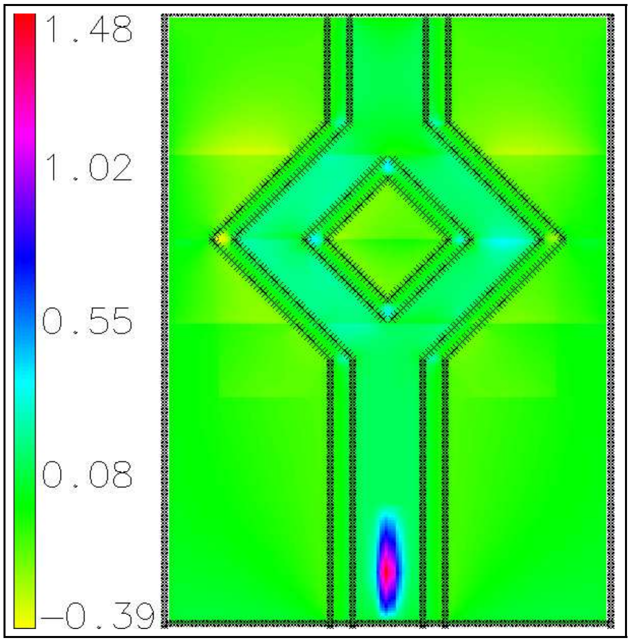

Figure 19: Error distribution [m] of DTM of the synthetic braided river interpolating with RST from data points along the breaklines and the boundary of the region. [Crosses indicates the ’surveyed’ points.]

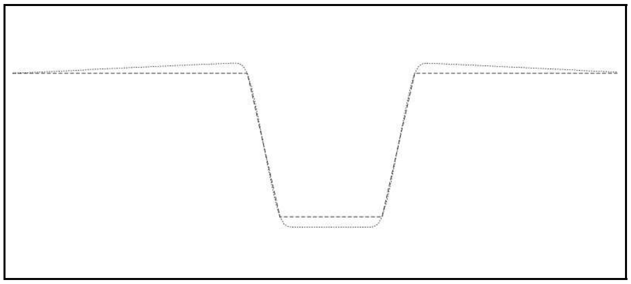

Figure 20: Error distribution along an interpolated transversal cross-section in the straight downstream reach compared with the corresponding synthetic data. Interpolation was performed with RST from data along dry and wet breaklines and region boundaries.

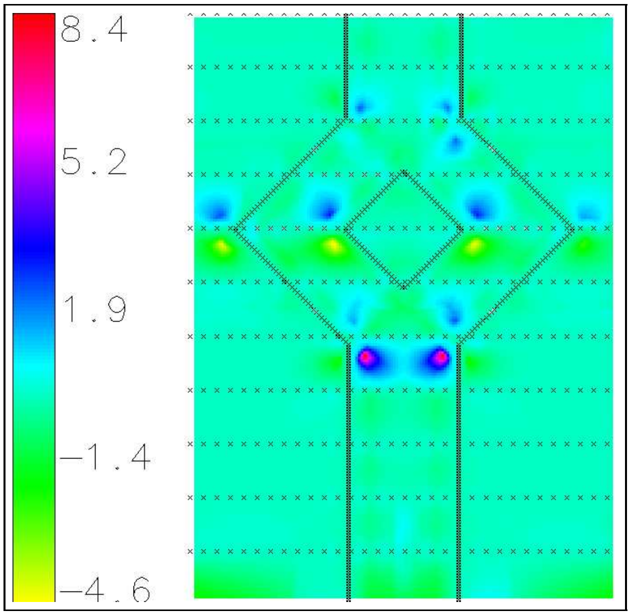

Figure 21: Error distribution [m] of DTM of the synthetic braided river interpolating with RST from data points along the dry breaklines and transversal cross-sections every 6 m (= 20 pixels). [The distance between two following points in a cross-section is 1.5 m (= 5 pixels). Crosses indicates the 'surveyed' points.]

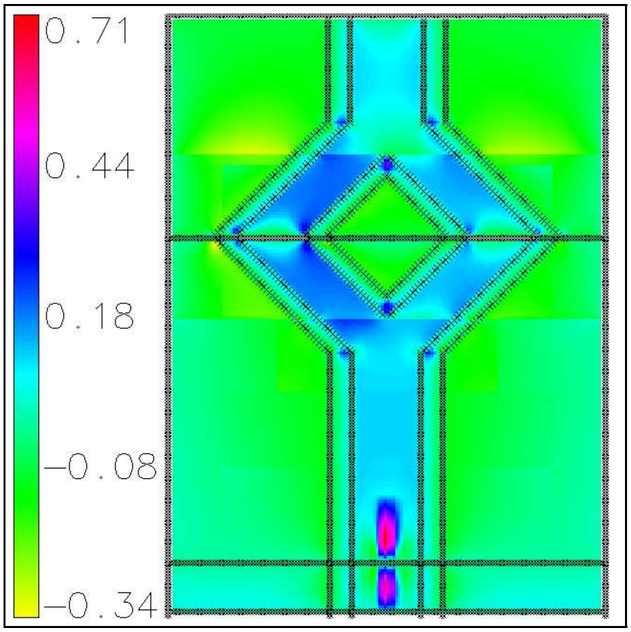

Figure 22: Error distribution [m] of DTM of the synthetic braided river interpolating with RST from data points along the breaklines, dry and wet, and some transversal cross-sections in correspondence of the slope changes. [Crosses indicates the 'surveyed' points.]

2.4.3 Application on straight single-channel river with semicircular cross-section

We then investigated if RST works well when the channel bed is not flat in the transversal direction but assumes a more natural shape.

So, we focused our attention on the synthetic DTM representing a straight single-channel river with semicircular cross-section (fig. 3), and 'surveyed' only transversal cross-sections. The distance between two 'surveyed' sections was 6 m (= 20 pixels) while the distance between two following points in a cross-section was 0.3 m (= 1 pixel). Just to have an idea of the physical dimensions, the channel width is 11.4 m (= 38 pixels) and the maximum channel depth is 5.7 m (= 19 pixels).

We set smooth=0, tension=40 (i.e. the default value), no anisotropic factors (to be congruent with interpolations showed in sect. 2.4.2), segmax=2 and npmin =10. Segmax was set so low in order to calculate the spline function in every 2 pixels, hence to localize the interpolation; note that it was possible due to the modest number of data points. The value of npmin was chosen so that, when we interpolate in a point between two sections, such point is influenced by points in both the sections, and more we are close to a section the influence is strong.

This solution is characterized by errors in general lower than 80 cm, but localized errors greater than 1 m are present (fig. 23). Hence we tried to increase npmin and tension, but the quality of the interpolation get worse in both cases.

We then tried to thin out points along the sections (1 point every 1.5 m = 5 pixels). The error increases especially close to the sections, parameters values being equal, because only 7 data points are present along a section in the channel, hence data points on the floodplain influence the interpolated data in the channel. Because lower npmin values are not reasonable, lower tension value (= 10) improves the result. The error is in general lower than 35 cm, with localized peaks close to the channel banks (fig. 24). Warnings appear if you tried to lower the tension more.

Hence, it seems that RST is able to interpolate quite well from transversal cross-sections with irregular shape if data are sufficiently dense. However, a deeper analysis with more natural river cross-sections will be performed in the near future.

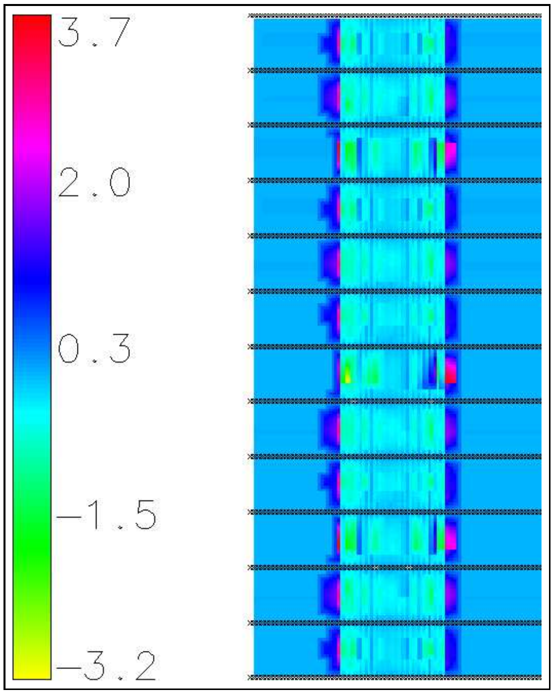

Figure 23: Error distribution [m] of DTM of the straight river with semicircular section interpolating with RST from dense data point along transversal cross-sections. The distance between two following points in a cross-section is 0.3 m (= 1 pixel). [Crosses indicates the ’surveyed’ points.]

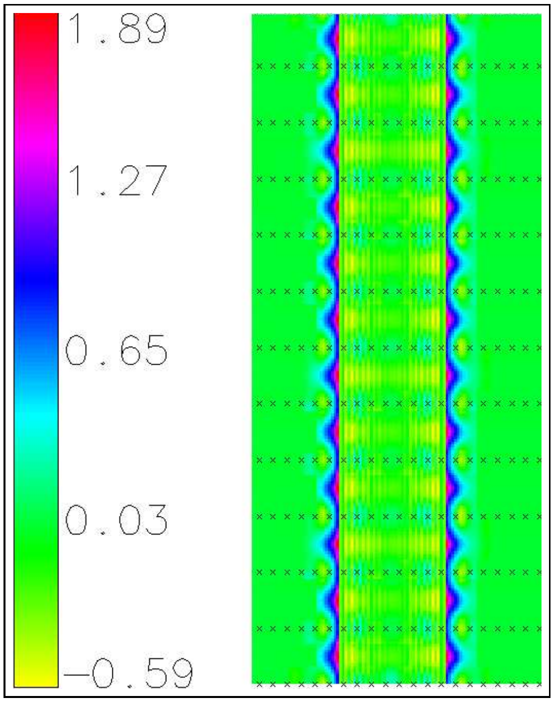

Figure 24: Error distribution [m] of DTM of the straight river with semicircular section interpolating with RST from less dense data point along transversal cross-sections. The distance between two following points in a cross-section is 1.5 m (= 5 pixels). [Crosses indicates the ’surveyed’ points.]

2.5 HEC-RAS

In the hydraulic engineering practice, to perform hydraulic calculations in natural rivers, the U.S. Army Corps of Engineers's River Analysis System (HEC-RAS) software is often used [7].
Such software also allows to interpolate between surveyed transversal cross-section data, in order to reproduce the ground surface in more detail and so to perform more accurate hydraulic calculations.

The interpolator is based on a linear model as graphically depicted in figure 25. It consists of lines that connect the coordinates of the upstream and downstream cross-sections.

Five master lines are automatically attached between the two cross-sections, in particular between the ends of the cross-sections, the points identifying the main channel banks (red dots in fig. 25), and the main channel thalweg, i.e. the lower elevation point, in figure 25 corresponding to 4 green lines and 1 red line along the channel thalweg. Additional master lines can be added to connect features that it is known should be connected, as the longitudinal bank in the hydraulic left floodplain in the example in figure 25.

Minor lines are generated automatically by the interpolation routines, by taking an existing coordinate in either the upstream or downstream section and establishing a corresponding coordinate at the opposite cross-section by either matching an existing coordinate or interpolating one. The coordinate value at the opposite cross-section is determined by computing the decimal percent that the known coordinate represents of the distance between master lines and then applying that percentage to the opposite cross-section master lines. The number of minor lines will be equal to the sum of all the coordinates of the upstream and downstream sections minus the number of master lines.

Interpolation at any point in between the two sections is then based on linear interpolation of the elevations at the ends of the master and minor lines.

When the geometry between two surveyed cross-sections does not change linearly, then the interpolated cross-sections will not adequately describe the real surface. It happens when you need to interpolate between cross-sections in correspondence of confluences and bifurcations, as required studying even the simplest braided river. An example is reported in figure 26.

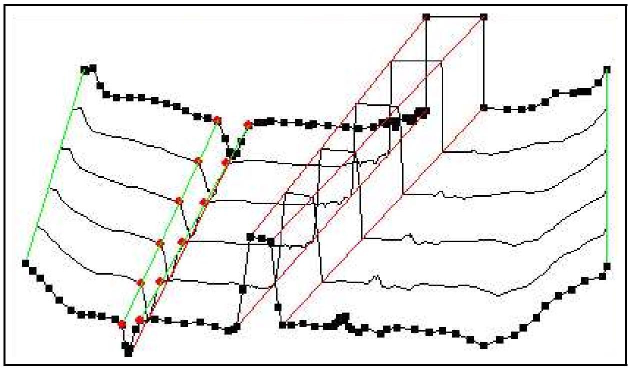

Figure 25: Example of interpolation between two cross-sections of a natural (not braided) river with HEC-RAS. Note the levee on the hydraulic left floodplain. [Water flows from up to down]

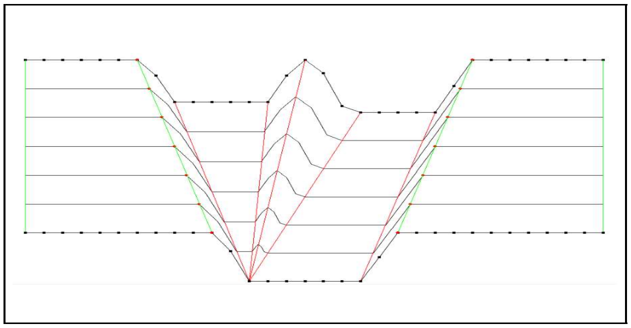

Figure 26: Interpolation with HEC-RAS in correspondence of a confluence. [Water flows from up to down]

3 Conclusions

A quick and economical survey is investigated to monitor the evolution of a braided river with ground topographic survey. Starting from synthetic DTM, different survey points and different interpolation methods are tested in a didactic approach to reproduce the braided river geometry.

First of all, we tested a software used in the hydraulic engineering practice, HEC-RAS, interpolating from significant transversal cross-sections of the synthetic braided river DTM. And we found that HEC-RAS software is not able to interpolate in a reasonable way in presence of confluences or bifurcations, i.e. between cross-sections of a braided river.

Hence, we started applying the simplest and most available interpolation method, Inverse Distance Weight method (IDW), to the synthetic braided river DTM through GRASS 5.3. But we ends up that such method needs a huge amount of data, on a regular grid if possible, also to reproduce a regular straight channel. Because this is not a realistic condition if you want to survey a reach of a braided river with ground techniques, we looked at Spline, Regularized Spline with Tension (RST) in particular.

We applied RST to the same synthetic braided river DTM and observed that it works better than IDW interpolating from sites along cross-sections. In fact, RST needs less sections to well reproduce the synthetic surface. However, the amount of observed data required is always relevant. To limit the number of cross-sections to survey, dry and wet break-lines, i.e. the lines that identify the transversal slope change between floodplain and the channel bank and between the channel bank and the channel bed respectively, are needed.

Hence, in a simplified braided river such the synthetic one, the topographic survey may be optimize surveying wet and dry break-lines and cross-sections at least in correspondence of the sharp longitudinal slope changes.

We also investigated if RST works well when the channel bed is not flat in the transversal direction but assumes a more natural shape. We performed interpolations from transversal cross-sections on a synthetic DTM representing a straight single-channel river with semicircular cross-section, obtaining good results.

To perform a good interpolation, however, spline parameters are to be set carefully. In particular, we set smoothing equal to zero because we have supposed an high reliability of observed data; anisotropic factors were set to zero due to the not unique anisotropy's direction in a surface like braided river; tension,segmax and npmin were tuned in every interpolation so to minimize the errors.

Note that, for braided river applications, the shape of the surface is more important than high data accuracy, because the data may have an error equal to the average grain size of the sediments (of the order of 10 cm). Obviously, it is important to look not only at the errors value but also at the error sign.

In the near future we will investigate how optimize a topographic survey of a braided river with more natural cross-sections shape, trying to avoid the survey of the wet break-lines because they are not always well defined in field.

Moreover, interpolations from cross-sections of variable spacing along the section, in function of the importance of the area, will be performed. In fact, through GPS cinematic survey it is natural to obtain more dense data points in complex area and more spread information in uniform zones.

And kriging method will be analysed with an appropriate analysis and compared with spline.

References

[1] Benciolini, B. Il metodo degli elementi finiti e le sue applicazioni ai modelli digitali delle altezze. *I Sistemi Informativi Territoriali* L. Mussio e F. Crosilla Eds. CISM Udine, 153-184, 1992.

[2] Crippa, B., & Forlani, G. Il calcolo con il metodo degli elementi finiti. *Ricerche di geodesia, topografia e fotogrammetria*, CLUP Ed., 92-137, 1990.

[3] Mitas, L., & Mitasova, H. Spatial Interpolation. In: P.Longley, M.F. Goodchild, D.J. Maguire, D.W.Rhind (Eds.), *Geographical Information Systems: Principles, Techniques, Management and Applications, GeoInformation International*, Wiley, 481-492, 1999.

[4] Mitasova, H., & Mitas, L. Interpolation by Regularized Spline with Tension: 1. Theory and Implementation. *Mathematical Geology*, 25(6), 641-655, 1993.

[5] Neteler, M., & Mitasova, H. OPEN SOURCE GIS: A GRASS GIS Approach. Kluwer Academic Publishers, 2002.

[6] GRASS 5.3 Reference Manual
*http : //grass.itc.it/gdp/html-grass*5

[7] HEC-RAS web-site
http : //www.hec.usace.army.mil/software/hec-ras/hecras-hecras.html