

DEM optimization for hydrological modelling using SRTM for the 'Pantanal' region, Brazil

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DEM optimization for hydrological modelling using SRTM for the 'Pantanal' region, Brazil.

by

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A los que estuvieron cerca ...

... con su corazón

ABSTRACT

The SRTM (Shuttle Radar Topographic Mission) was launched in February 2000. The mission obtained elevation radar data on a near-global scale to generate the most complete high resolution digital topographic database of the Earth. This database allowed to generate DSMs (Digital Surface Models). A DEM (Digital Elevation Model) was optimized based on this DSM for the 'Pantanal' region, Brazil, an area with an extensive and complex drainage network in a terrain with very gentle relief. The optimization process had to represent the three main terrain features in the DEM. The correction must be applied in a determined order starting to remove vegetation influence first, to pull down the drainage network and finally a height correction for flooded areas. A qualitative method was used to assess the results. The comparison between the final DEM and the satellite images shows a very good representation of the drainage network and the flooded areas. The derived drainage obtained represents the flow in the streams towards the outlet of the DEM in a realistic way. The assessment allows to conclude that the obtained DEM is a realistic representation of the complex characteristics of the terrain in the 'Pantanal' wetlands. It is hoped that the results of this research will be useful as input for further modelling activities in order to develop tools for sound policy decision-making.

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(http://www.alterra-research.nl/servlet/page?_pageid=780&_dad=portal30&_schema=PORTAL30)

To fulfil the overall objective of the project, support the wise use of the plains of the Pantanal-Taquari river catchments, Brazilian and Dutch partner started to collaborate during a kick-off meeting in Corumba (Brazil) on 19-20 August 2003. The data and the information presented were obtained during this seminar by the Brazilian partner EMBRAPA is highly appreciated. It is hoped that the results of this research will be useful as input for further modelling activities in order to further develop tools for sound policy decision-making.

To Pablo, with whom will last a long time a great friendship.

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1. Introduction

1.1. General description

There are lots of ways that people make use of topographic data. Scientists use information about topography to help in their studies of plants and animals. Elevation information provides clues about soil types, and can tell you how the surface of Earth changes due to the actions of glaciers, rivers, and the processes of mountain building and erosion. City planners use topographic data to help locate suitable places for structures or recreation. Aircraft pilots require accurate topographic information for flight planning and navigation, and the military requires precise topographic information for training and real time operations.

For various parts of the world, maps of Earth's topography are limited, inaccurate, or nonexistent. For example, many mountain chains, inhospitable deserts, and dense tropical rain forests have topographic coverage that is totally inadequate mainly because of the difficulty in getting to these locations.

Although it is possible to get modern instruments today (as electronic theodolites and GPS), the traditional methods for ground surveying need a laborious process to generate terrain maps. Aerial photogrammetry also has difficulties related to a good visibility and the logistics involved on operation aircraft.

During many years different missions have obtained spatial data viewing the Earth from space. The resulting mosaic of different kinds of data sources with a multitude of horizontal and vertical datums, accuracies, formats, map projections and resolutions is hardly a uniform and reliable dataset. A major restriction is also the impossibility to assess the accuracy of the resulting derived products. A recurring problem with the existing inventory of topographic data is the inhomogeneous data quality when attempting to integrate the acquired data into a global dataset. As a consequence the comparability of results suffers greatly. Constant data quality from a single data source is, therefore, imperative but with SRTM this is not a problem.

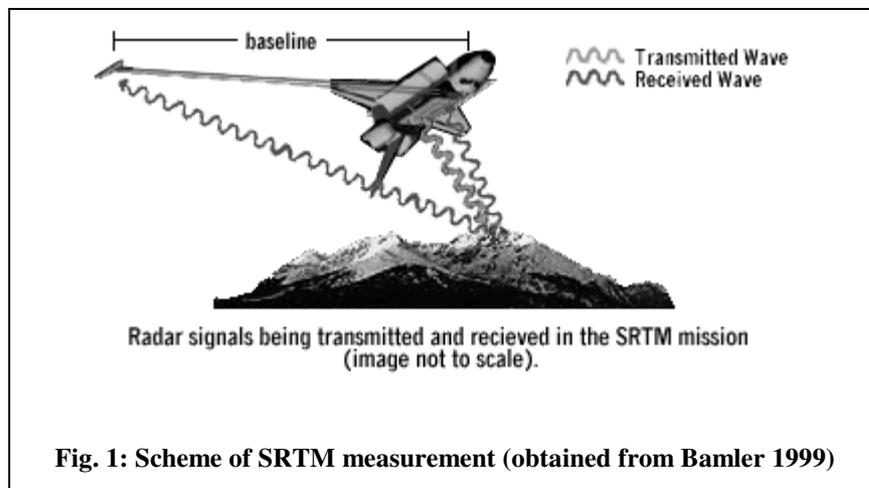
The 'Shuttle Radar Topography Mission' (SRTM) was launched in February of 2000. A survey of the land masses were made between 60° North and 58° South latitudes. The objective of the SRTM was to obtain elevation radar data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth. The SRTM generated consistent, comprehensive topographic data and radar images to model the terrain and map the land of most of the inhabited surface of the Earth. The instrument used is the 'Synthetic Aperture Radar' (SAR) applying interferometry techniques which allows generation of three-dimensional images of the Earth's surface with high resolution independent of the sun's position, the weather and surface contrast. The

interferometry measurement mode was conducted for both C and X bands, using a special configuration based on secondary receiving antennas mounted onto the tip of a 60 meters long, deployable, stiff, boom structure perpendicular to the direction of the space shuttle, to build the baseline. The measurement obtains the terrain height to derive the surface topography in addition to surface imaging. The single pass SAR interferometry of SRTM gave a coherent DEM measured by a single system during a mission of 11 days. It is a near global and consistent DEM based on one geodetical reference system. Further information about the mission is available at <http://www2.jpl.nasa.gov/srtm/>

The high sensitivity of the SAR phase to range is exploited. SAR's are used to image the same ground area from two (almost) parallel orbits (Fig. 1). A typical spatial separation (baseline) of the orbits is in the order of 10 m – 500 m. In the case of repeat-pass SAR the two SAR images are taken at different times (e.g. several days apart) possibly by the same radar. Single-pass interferometry, on the other hand, requires a dual channel radar system with a transmit/receive master antenna and a receive-only slave antenna. In either case the two SAR's or channels measure slightly different ranges R_1 and R_2 for any ground point. Hence, the corresponding image pixels, although equally 'bright', exhibit different phase. The phase difference (or interferometric phase) ϕ of two corresponding pixels is related to the range difference (parallax) via

$$\phi = p \frac{2\pi}{\lambda} (R_1 - R_2)$$

where $p = 2$ for repeat-pass and $p = 1$ for single-pass interferometry, respectively. This phase is measured pixel-wise by i) co-registration of the two SAR images to within a small fraction of a pixel and ii) complex conjugate multiply of the registered images. Every pixel of the resulting interferogram carries phase, i.e. parallax, information –even in areas of low or no contrast. From this two-dimensional phase field the Digital Surface Model (DSM) of the imaged area can be computed after the 2π ambiguity of the phase measurement has been removed by a procedure called phase unwrapping (Bamler 1999).



The great advantages of SRTM are its homogeneity, overlap from ascending and descending paths, near global coverage, excellent resolution, low cost and a non-restricted availability.

The geometric specifications are: (SRTM C-SAR)

Spatial Resolution, 90 x 90 m

Horizontal Datum, WGS 84

Vertical Datum, WGS 84 ellipsoid

Physical Units, meters

Accuracy specifications:

Horizontal Accuracy (90 % circular error)

Absolute, 60 m

Relative, 45 m

Vertical accuracy (90 % linear error)

Absolute, 16 m

Relative, 10 m

Using the information about the distance between the two antennas and the differences in the reflected radar wave signals, accurate elevation of the Earth's surface can be calculated. These procedures allowed to generate a near global Digital Elevation Models (DEMs), covering approximately 80 % of the Earth land mass.

1.2. Digital Surface Model (DSM)

The SRTM allowed to create an interferogram integrated by two-dimensional phase field. The unwrapping phase procedure removes the 2π ambiguity of the phase measurement and DSMs could be obtained.

The radar technique used bands measured in centimeters. The K (1 cm), X (3 cm) and C (5.6 cm) bands (for centre wavelength) have a reduced canopy penetration at these wavelengths (Hess, 1990). The C-SAR band from SRTM operated in 5.6 cm wavelength. Therefore a DSM created in this way contains data received from the first feature imaged at the Earth. Mayer (2000) mentions that a DSM represents a complementary data source to images based on spectral reflectances in remote sensing information processing and Smith (2003) defines a DSM as a representation of the upper surface of the earth, or features on that surface.

A DSM is a representation of any object large enough to be resolved. This includes buildings, vegetation, roads as well as natural terrain features. These features can be a problem depending on the applications in which the DSM is used. For instance, hydrological treatments needs to remove the objects present at the surface.

1.3. Digital Terrain Model (DTM)

A Digital Terrain Model (DTM) is a computerized representation of the Earth's terrain. DTM is either described by a wire frame model or an image matrix in which the value of each pixel is associated with a specific topographic height. Commonly, terrain heights are expressed as grey values on a scale ranging from black (minimal) to white (maximal height). The addition of shading, assuming a light source illumination the DTM from the upper left corner, gives an improved visual representation of the topographic relief.

The georeferenced three-dimensional product can be complemented by a coordinate system and presented in a 2D map projection or as a 3D perspective view. In combination with other spatial data it is an important database for topography-related analyses or 3D video animations.

1.4. Digital Elevation Model (DEM)

Digital Elevation Models (DEM) and DTMs are in essence the same. DTM is actually a more generic term for any digital representation of a topographic surface. DEM is widely used to refer specifically to a raster or regular grid of spot heights.

1.5. The 'Pantanal' region

This region is located in the south-west of Brazil close to Bolivia in South America. It is possible to divide the region in three main sectors. The 'Planalto' is between 250 and 750 m.a.s.l., the escarpments between 180 and 250 m.a.s.l and the 'Pantanal' wetlands between 80 and 180 m.a.s.l. The area of the 'Pantanal' wetlands is around 190.000 km². The 'Pantanal' region is characterized by a low population density but the population has increased especially in the 'Planalto' area since the 1970's. The 'Planalto' is dominated by a soil highly erosive and the increase of the population could transform the wetlands in an unstable system with an increase of the area affected by permanent inundation. The population in the wetlands is scarce. The ecosystem is composed of 300 species of fishes, 95 kinds of mammals, 167 kinds of reptiles, 35 kinds of amphibian and 650 kinds of birds. The economic activities are restricted mainly to cattle breeding.

1.6. Research Question:

The region shows lots of changes in relation to its surface water during the year due to:

- a) Two different rainfall periods (wet and dry season).
- b) Marshy areas in an inter-tropical region with very gentle relief.
- c) Many depressions close to each other. A depression covers an area of until 1 sq. km distributed in an area close to 40.000 sq. km.

The main research question is how to combine data from different sources to improve the quality of the SRTM Digital Surface Model (DSM) for hydrologic modelling?

1.7. Hypothesis:

It is possible to improve the quality of the Digital Surface Model (SRTM, C-band 90 m spatial resolution) for hydrological modelling if it is integrated with:

- a) Optical images having a spatial resolution better than the spatial resolution of the DEM for dry season.
- b) A suitable vector file containing the detail and the complexity of the existing drainage network.
- c) Optical images that allow to consider relevant (temporal) features at a regional scale.

1.8. Objectives:

To optimize a Digital Surface Model (DSM) considering three main terrain features (vegetation, drainage network and flood areas), to obtain a suitable Digital Elevation Model (DEM) for hydrological modelling. The application will be developed over the lower "Pantanal" region, Brazil.

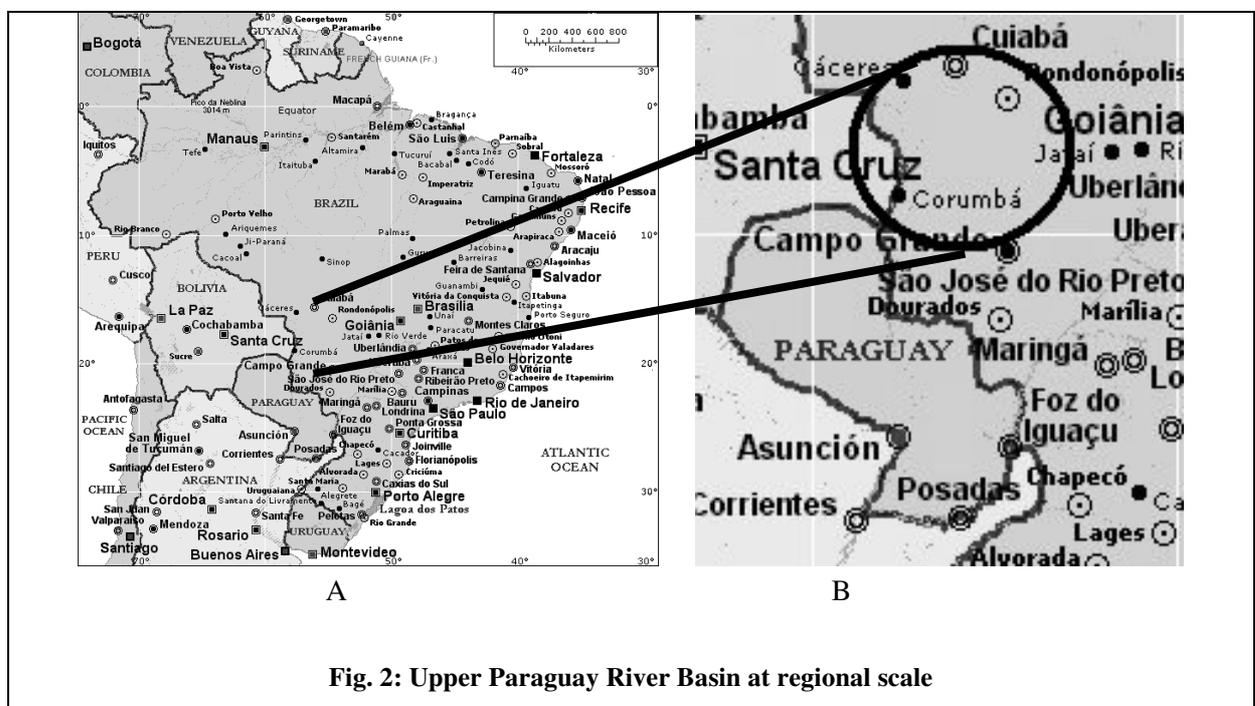
To integrate optical sensor data from different sources to improve the quality of the DTM.

To improve the knowledge with regard to the distribution of permanent and temporal lakes and level of the swamps in the study area.

2. Study Area

2.1. Regional description:

The Upper Paraguay River Basin is situated between 14 and 22° South latitude and between 53 and 55° West longitude and spreads towards the south; 75 % of the total area (400.000 km²) is on Brazilian Territory. Fig. 2 shows the Upper Paraguay River Basin and the 'Pantanal' region.



The Upper Paraguay drains an area close to half a million square kilometers. According to topographical elevation this basin can be subdivided in three physiographic units (Girard 2003),

- A 'Plateau' between 250 – 750 m.a.s.l. is the headwater region. A flat undulating plain constitutes most of the Plateau and is covered by a more or less open savanna (called 'cerrado') that is now extensively used for agriculture and cattle ranching.
- Escarpments at altitudes ranging from 180 to 250 m. This is a small region with generally steep slopes that is covered by dense forest.
- The 'Pantanal' extends from less than 100 to 180 m.a.s.l. It is about half the size of the Plateau. It is a low relief plain with a hydraulic gradient not exceeding 15 cm/km. Many large rivers, such as the

'Paraguay', the 'Cuiaba', the 'Sao Lourenco', the 'Piquiri', the 'Taquari', and the 'Negro' cross this vast plain. Fig. 3 shows a picture of the 'Pantanal' region.



Fig. 3: Typical river in 'Pantanal' region.

The 'Pantanal' wetland is a vast evaporation plain and sediment accumulation surface occupying an immense sedimentary depression. The 'Pantanal' is essentially a huge, gently sloping fan that receives runoff from the upland watershed (the Plateau) twice its size and slowly releases the flood pulse of those waters through a single, downstream channel, the Paraguay River (Girard, 2003).

The 'Pantanal' (marsh) covers an area of about 190.000 km². It may be divided in two regions based on the frequency and extend of flooding (UNESCO, 1973)

First, marshy areas with permanently impeded drainage (Fig. 4). The marsh is fed by major and minor rivers and small lakes connected (or not) by temporary channels. This area comprises less than 20.000 km². Second, intermittently flooded areas, subdivided into flooded areas by major or minor rivers and areas flooded by rainfall where the drainage network is inadequate. This is also called 'Pantanal' but is not a marshy area.



Fig. 4: Marshy and extended areas in 'Pantanal' region.

Marshy areas are extensively formed by small lakes and abandoned old meanders partially or completely covered by grass. Lakes and old meanders in general contain during the year a few meters of water and have grass growing from the bottom that sticks out to the surface. The surface of the lakes is not visible during the dry period because of the green cover. However, it is possible to find a fluid layer under the apparently quiet or inexistent lake. The water can run slowly, about of 1 to 5 cm/sec.

The intermittently flood areas are formed by depressions and channels. They become active depending on the height of the flood in each river every year. When the flood decreases the water runs downstream by small dells, channels or 'vazantes'. UNESCO (1973) defines 'vazante' like a drainage line from an area seldom flooded to a 'pantanal' area or to a river downstream. It is a strip of some kilometers wide having a moderate slope in longitudinal direction but without a well-developed channel. In general, a 'vazante' has a green cover at his bottom. When a 'vazante' has a well-defined cross section for a long distance it is called a 'corixoe'. The 'corixoes' would be until three meters below the surrounding surface and after a certain distance they may end in a 'vazante' again. In this way, water moves very slowly through the lowland to reach the main rivers.

2.1.1. Climate

The Atlantic subtropical anticyclone is situated on average at 30 °S latitude. The anticyclone cell moves slightly towards the north direction in winter season and it extends to the west over the

South American continent. The presence of the anticyclone over the continent impedes storm development. The anticyclone cell reduces his intensity from September when the cell moves to the south and keeps the centre over the Atlantic Ocean. The anti-clockwise air circulation in the anticyclone cell allows the winds to enter the continent between September and March. The winds bring humid air masses starting the rainy season. Due to this anticyclone feature rainfall occurs in extensive areas in NE to SW direction from the East of Brazil till the centre of Argentine throughout Paraguay and Bolivia.

According to Köppen's classification, the 'Pantanal' area is classified as Aw. The description from Barry (1999) is that 'A' corresponds to a tropical rainfall climate. There is a seasonal alternation between humid and dry air masses. The 'w' means that it has a dry season during winter. The other feature is that the monthly mean temperature is higher than 18 °C in the coldest month of the year in spite of a temperature drop as low as 0 °C for short periods. Temperatures near 0 °C occur during the winter season when some intense cold weather systems can reach south Brazil from the south.

An example of mean temperature values could be Cuiaba city with 27.4 °C in December and 21.4 °C in July. (Girard 2003).

The average rainfall varies between 1080 mm (to the South of the region) to 1250 mm (to the North) per year and the evapo-transpiration varies between 1100 and 1300 and surpasses rainfall during at least 6 months (Girard 2003).

The intensity of the rainfall in general is high and it is common to find daily values of 40 mm (Barry, 1999).

2.1.2. Geology

The UNESCO report (1973) describes that the Upper Paraguay River Basin is underlain by the Basement Complex consisting of schists, quartzites, amphibolites, gneisses and granites. This complex rises to the surface in the north-west, in the south west and near 'Corumba' but in some areas the basement is situated at a depth of 227 m at 'Sao Sebastiao' Farm (19°21' S, 56°33' W), 320 m depth at 'Piquiri' Farm (17°16' S, 56°19' W) and 420 m depth at 'Sao Bento' Farm (18°10' S, 56°18' W).

Krol (1970) made a description of the stratigraphy of the Upper Paraguay River Basin. The classification distinguishes the Basement Complex, Cadieus Formation, Cuiaba Series, Jangada Group and Puga Formation, Araras Group, Corumba Group, Alto Paraguay Group, Jacadigo Series, Chapada Series, Aquidauana Series, Passa Dois Series, Sao Bento Series, Parecis Series and Quaternary Deposits. The 'Pantanal' area belongs to the Quaternary Deposits class.

According to Krol (1970) the 'Pantanal' Quaternary deposits covers the interior of the Upper Paraguay River Basin. The information about the lateral variations in sediments is not extensive. The sediments mainly consist of sand and argillaceous material underlain by a conglomerate of sub-

angular quartz pebbles. Areas surrounding the 'bacias' (lakes or seasonally filled depressions) are sandy whilst the sediments in the 'bacias' are more argillaceous and rich in humus material. In wide depressions there is a thin layer of loam covering the sand. Some recent deposits often consist of limonite and it is also possible to find important amounts of alkaline salt deposits.

Two boreholes in Quaternary deposits mentioned in Krol (1970) near to the 'Taquari' River area show the following sediments stratigraphy:

To the North-East of 'Corumba' (18°10' S, 56°18' W).

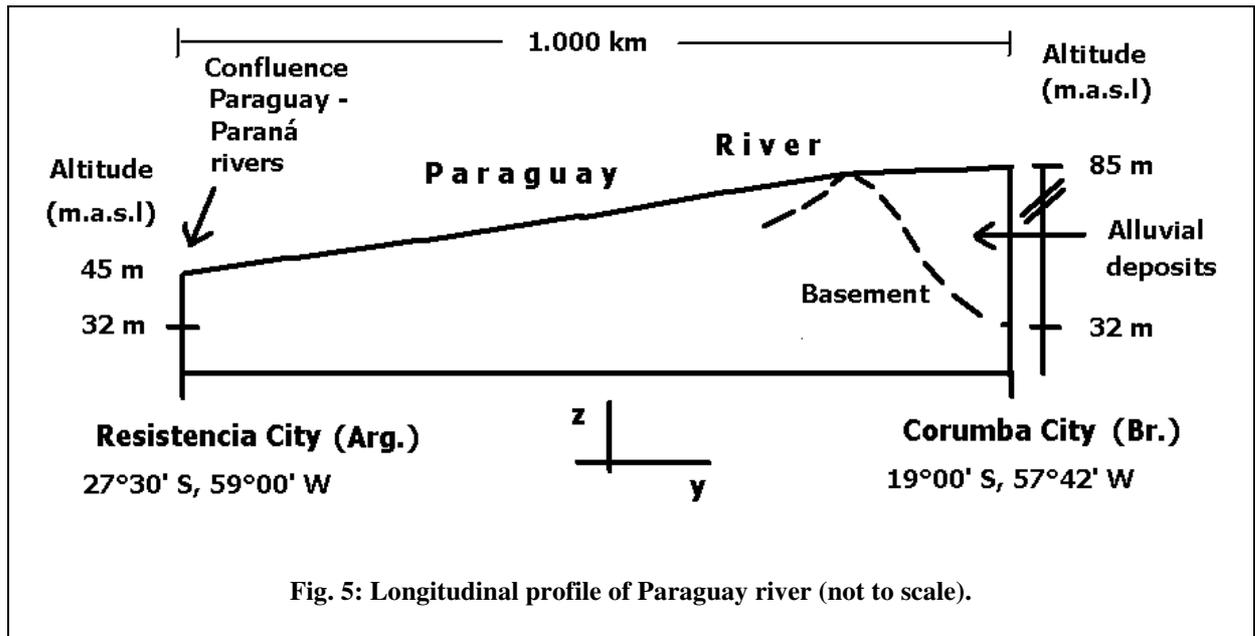
0 – 50 m, quartz, quartz sand, fine-medium, subangular, rounded, well sorted;
50 – 100m, quartz sand, poorly sorted, fine to coarse ferruginous cementation;
100 – 200m, fine yellow-brown sand, ferruginous cementation, canga traces, well sorted in the first 50 m;
200 – 217 m, soft plastic silty clay

To the South-East of 'Corumba', in 'Fazenda Sao Sebastiao' (19°21' S, 56°33' W)

0 – 200 m, brown clayey sand, fine to coarse, subangular, rounded, grading into;
200 – 213 m, conglomeratic deposit
213 – 227 m, schist and gneiss of the Basement Complex.

UNESCO (1973) states that the 'Pantanal' is possibly still a deposition area. This assumption find a reason in the uplift zone near to 'Baia Negra' two hundreds kilometers downstream 'Corumba'. This uplift led to deposition of a huge amount of sediments upstream. The floor of the 'Pantanal' is located at 'Corumba' below the alluvial deposits and its altitude is 13 m less than the altitude of the confluence of the 'Paraguay' and the 'Paraná' rivers situated close to one thousand kilometers downstream 'Corumba' (Fig. 5).

Assine (2004) described also the relations between faults and sediments in the 'Pantanal' region. He mentions the abrupt change in the 'Paraguay' river direction at 'Corumba'. A fault in E-W direction forces the river to change its course from the north towards the east. Assine also refers to the Transbrasiliano Lineament recently recognized (since 1998). It is a remarkable NE-SW tectonic feature striking from the equatorial Atlantic margin to the Andes, crossing obliquely across the 'Pantanal' wetland. The lineament defines the south limit of the active sedimentation region of 'Taquari' river.



2.1.3. Vegetation

The vegetation in the Upper Paraguay River Basin can be divided in three main sub-regions based on the UNESCO (1973) classification:

The 'Chaco': on the south portion extending from Bolivia and Paraguay. It is possible to recognize three different landscapes. Alluvial lowlands periodically inundated by local rainfall and vegetation depends on the degree and duration of the flood events. River terraces in which vegetation varies in accordance with the groundwater levels and isolated hills with the vegetation adapted to the rock type.

The 'Cerrado': small trees with thick bark, large leaves and an understorey of grasses which grow on deep, permeable sandy soils. The vegetation can be divided in two varieties:

'Cerrado', a formation with trees, seldom higher than five meters, closely-spaced but with their crowns just not touching, and usually no bushy undergrowth.

'Campo cerrado', which consists of twisted, gnarled, well-spaced trees less than five meters in height, interspersed with multi-branched bushes and herbaceous vegetation.

The 'Cerrado' area is a landscape of 'vazantes' covered by 'campos de capim-mimoso' surrounded by large groups of trees. The most important variations in this landscape are:

- 'Campo cerrado' interrupted by occasional grass-covered 'vazantes'.
- Many 'vazantes' bordered by narrow terraces are covered by 'cerrado' trees; near the confluence of the 'Sao Lourenco', 'Cuiaba', 'Piquiri' and 'Taquari' rivers with the 'Paraguay', 'baias', small 'corixoes' and large 'vazantes' surrounded by groups of different woodlands are always accompanied

by some small 'carandas' on abandoned termite-hills. Very often these woodlands have an undergrowth of 'acuri', forming the 'acurizal' of those places that are more liable to flooding.

Transitional Forest: This forest is consisting predominantly of palm trees, grows in the extreme north of the Upper Paraguay River Basin.

2.1.4. Hydromorphology

UNESCO (1973) describes the stage of the present drainage network as a consequence of a collapse associated with tectonic movements occurred during the emergence of the Andes. The tectonic process gave rise to the formation of a big lake in the present Upper Paraguay basin, in an area that originally drained to the 'Parana' River located to the East the Paraguay basin. Alluvial deposits filled in the lake and these deposits form today's Pantanal.

The 'Pantanal' is a flat region having a gentle slope varying between 0.5 to 0.3 m/km from east to west and from 3 to 1.5 cm/km only from north to south (e.g. as along the 'Rio Paraguay').

There are river systems in the 'Pantanal' that show a converging drainage pattern (e.g. 'Piquiri', 'Rio Negro') and thus they transport less sediment than the streams that exhibit a divergent pattern (e.g. 'Rio S. Lourenco', 'Rio Taquari'). The last category transports large quantities of sediment and their banks are at a higher elevation than the surrounding alluvial plain.

The channel morphology in main and permanent rivers depends on the average annual floods, the regional slope and the type of alluvium. The channel morphology of the 'vazantes' and of the 'corixoes' depends on the extreme discharges as well as on other variables.

The average slope of the 'vazantes' generally is the same as the slope of the interfluvial areas. Locally, hollows carved by the flow in the channel bed cause minor negative slopes in the bed. The 'vazantes' flow along relatively straight courses with only few and wide curves.

The average slope and channel form of the 'corixoes' depends upon their origin: if they are former river beds the amplitude of their meanders approximates that of the rivers of the surrounding area; if they are produced by channelized flow of flood waters spread by rivers over their flood plains, then their courses are less meandering than the main rivers.

2.1.4.1. Surface Runoff

The isolated escarpments in the Upper Paraguay River basin are covered in general with trees and other dense vegetation. When the slope changes from steep to gentle at the start of the escarpments the vegetation and organic material impede surface runoff. Due to the infiltration process the water drains as sub-surface and groundwater flow. The water in general emerges at a certain

distance of the escarpments. As a consequence there are no well-defined channels near to the escarpments.

The 'Pantanal' wetland is characterized by a very gentle slope and the area is mainly covered with vegetation. The combination between gentle slope and vegetation implies a delayed surface runoff. Specifically for 'Pantanal' area UNESCO (1973) states that the surface runoff after each rainfall event is quite low because of infiltration encouraged by the gentle slope and the grass cover. During the dry season, for some areas, there is a soil moisture deficit due to transpiration up to a considerable depth. The rainfall is absorbed in the soil during the beginning of the wet season. The intense rainstorms contribute to overland flow. However, the water runs a short distance if not infiltrated or retained by the grass to the closest dell, where it is added to delayed subsurface flow of the water from the surrounding area.

Where the infiltration rate is low ('Chaco' vegetation) the potential evaporation and transpiration losses would dry the dells before the end of the dry season mainly if the rainfall is below average. Where the infiltration rate is greater ('cerrado' vegetation) the dells quickly loses its water. This implies a minor evaporation loss. When the infiltration rate is high and the rainfall is above average the water table may reach the bottom of the dells and surface water may be maintained there throughout the year. The dells collect water from upstream and moves water downstream saturating the soil or infiltrating and evaporating until it is exhausted or until the dell empties into a river are called 'vazantes'.

2.1.4.2. Groundwater

The 'Pantanal' is not an impermeable marshy region but is remarkably rich in underground water, which is situated in the bedrock underlying the alluvial sediments (UNESCO, 1973).

Girard (2003) studying the 'Cuiaba' River area found that floods are the main groundwater replenishment mechanism. Groundwater recharge is also important to maintain floodplain channel flow during low water stage when the rivers do not receive direct contribution of the 'Cuiaba' waters through the 'vazantes'. Groundwater flow also maintains soil saturation in the depressed portions of the floodplain. The recharge volume will depend on the area of outcropping sand beds covered by flood waters, depth of the flood waters, duration of inundation and the hydraulic conductivity of the sand beds. A reduced flood peak will imply less groundwater.

2.1.5. Floods

The annual flood pulse is mono-modal and presents temporal and spatial variations (Girard, 2003).

Girard (2003) gives a description of the behavior of the flood event around the 'Cuiaba' River but perhaps it is possible to extend the same description in many similar places in the 'Pantanal' area. With respect to the 'Cuiaba' River, Girard states that at the beginning of the flood both local rainfall and a higher water volume of 'Cuiaba' River from upstream contribute to higher water levels in the floodplain. However the 'Cuiaba' River doesn't contribute water direct to the floodplain because the river is flanked by levees. The water reaches the floodplain through 'vazantes' but during the floods much of the levees can eventually be covered by water. While the floodplain is filled up, the water in the 'vazantes' usually runs from the river to the floodplain. During the flood, the flow direction could change several times in the 'vazantes', depending on the stage differences between the floodplain and the rivers. During the receding stage the main river levels drop and the 'vazantes' act to empty the floodplain waters into the rivers.

2.1.6. Paraguay and Taquari Rivers

The present work is focussing on the behavior of both the 'Paraguay' and 'Taquari' rivers. The Fig. 6 shows these rivers and the main villages along the rivers.

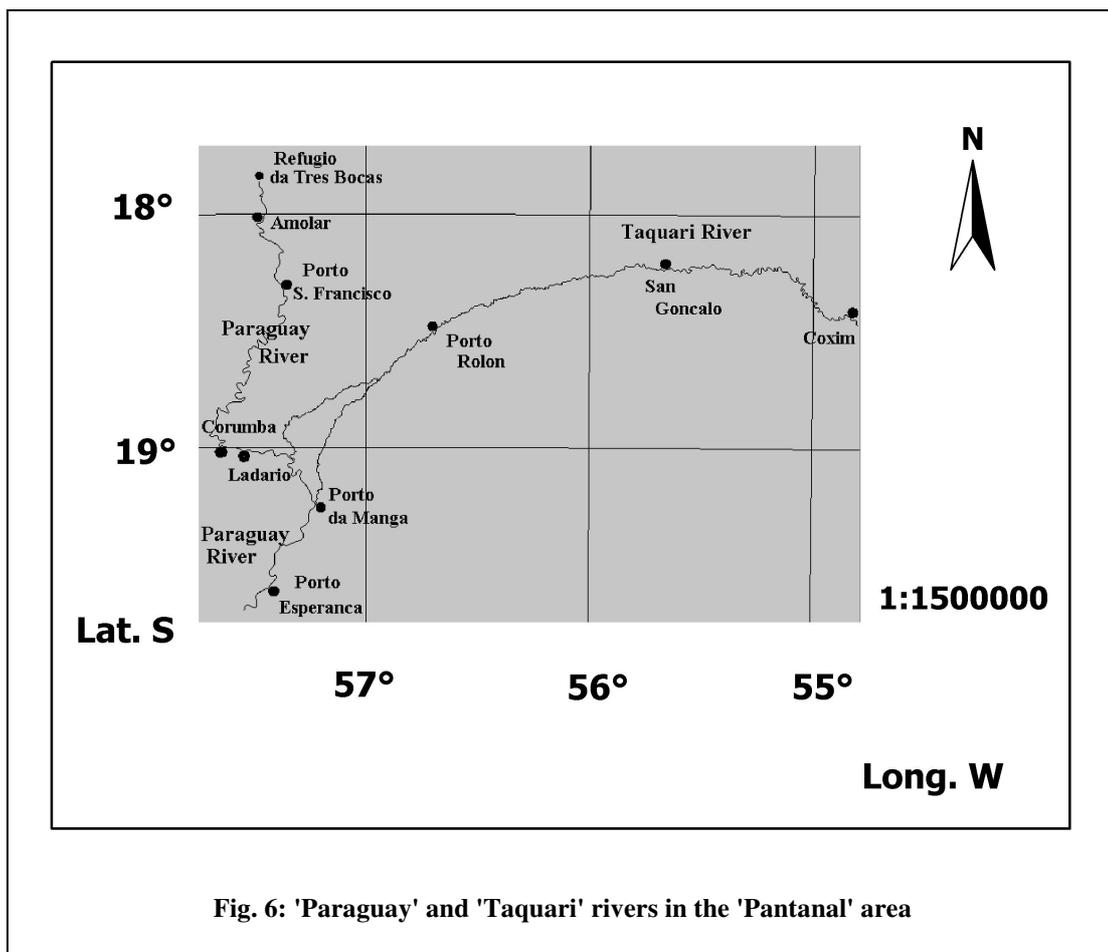


Fig. 6: 'Paraguay' and 'Taquari' rivers in the 'Pantanal' area

UNESCO (1973) describes the 'Paraguay' along its lowland course having built up 2-3 m high levees composed of fine alluvium often covered with trees and they are seldom inundated. These natural dykes force the small tributaries to flow over long distances parallel to the river before entering it. This drainage pattern is common along the river.

The values shown in tables 1 and 2 were obtained from UNESCO (1973) and characterize the main features of both rivers.

Paraguay:

Sector	1	2	3	4	5	6
'Porto S. Francisco' – 'Corumba'	146	71	300-400	76	280	410
'Corumba' – 'Taquari velho'	41	35	300	15	120	50
'Taquari "velho" – 'Porto Esperanca'	100	63	250-400	30	390	300

Table 1: Main features of the 'Paraguay' river.

Taquari:

Sector	1	2	3	4	5	6
'Pedro Gomes' – 'Coxim'	60	50	80	4	8	-
'Coxim' – 'S. Goncalo'	186	104	150-300	30	110	10
'S. Goncalo' – 'Porto Rolon'	153	120	150-400	30	120	-
'Porto Rolon' – Confluence with 'Paraguay'	110	84	150-60	12	-	300

Table 2: Main features of the 'Taquari' river.

References Tables 1 and 2

- 1_ Distances along the river bed (km)
- 2_ Straight distance (km)
- 3_ Width of the river channel at low water stage (m)
- 4_ Extent of water surface around the river channel at low water stage.
- 5_ Extent of water surface around the river channel at high water stage.
- 6_ Other 'Pantanal' areas around the river channel (in sq. km)

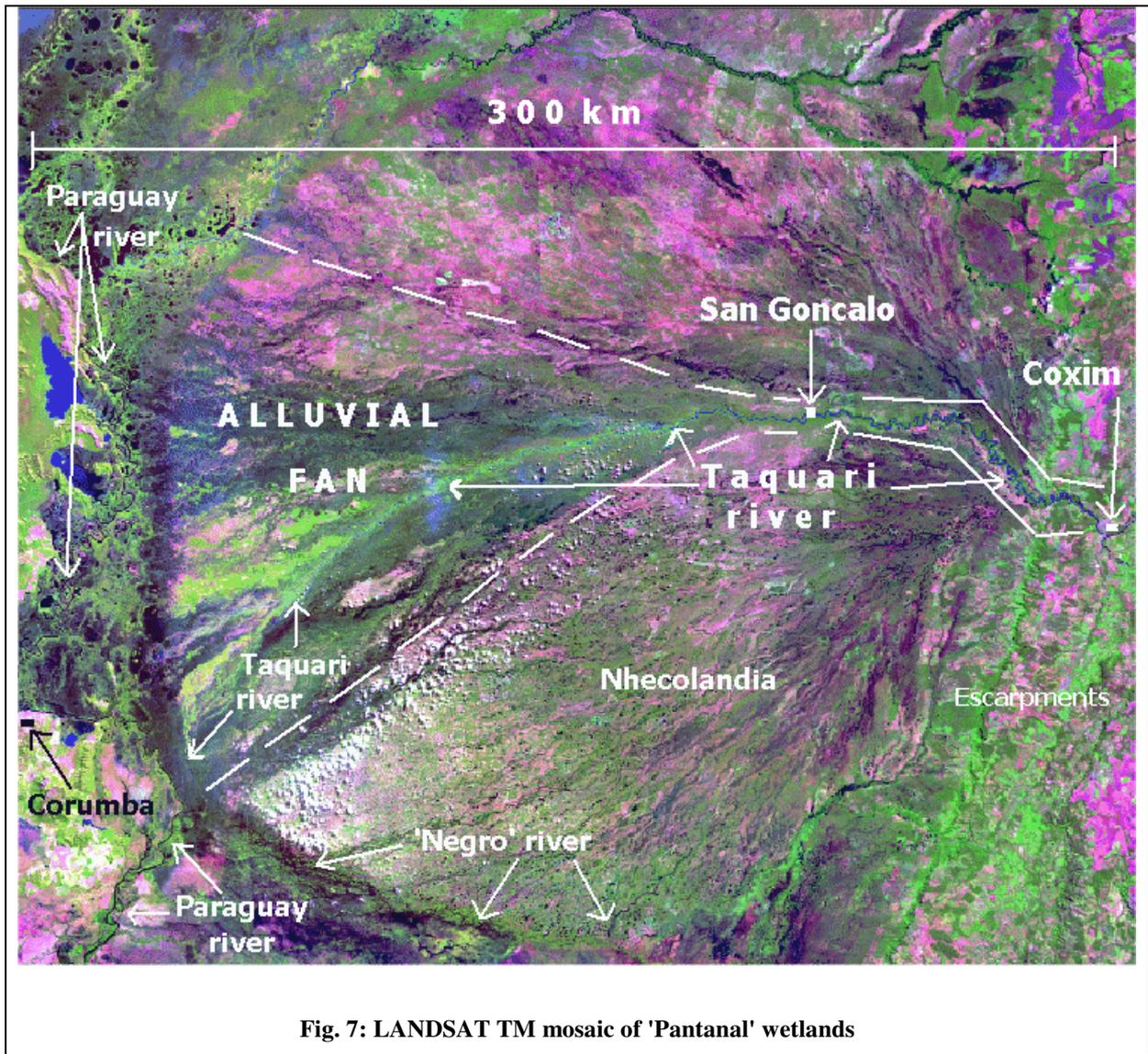
Table 3 shows longitudinal profile for 'Paraguay' and 'Taquari' river at a few locations.

Paraguay's sector	Slope (m/km)	Taquari's sector	Slope (m/km)
'Descalvados' – 'Porto S. Francisco'	0.05	'Coxim' – 'S. Goncalo'	0.45
'Porto S. Francisco' – 'Porto Manga'	0.065	'S. Goncalo' – 'Porto Rolon'	0.32
'Porto Manga' – 'Nabileque' outlet	0.026	'Porto Rolon' – 'Porto Manga'	0.17

Table 3: Longitudinal profiles.

The 'Taquari' river exhibit a divergent drainage pattern in the 'Pantanal' wetlands (Fig. 7). According to Assine (2004), in the upper fan, the 'Taquari' river is entrenched in ancient fan lobes and sedimentation takes places in a meandering belt confined by terraces up to five meters high. Tectonics could explain the entrenchment, but the true cause is still to be discovered. The 'Taquari' has a developed an extended alluvial fan in which the river discharges during flood. The alluvial fan starts approximate to 60 km downstream of 'Coxim' ('San Goncalo') and it extends until the fluvial plains which corresponds to the Paraguay river. Discharge measurements at 'Coxim' from the UNESCO project (1973) showed yearly average values of 260 to 280 m³/s. However, it is possible that UNESCO measurements had underestimated the yearly average values. Collinschonn (2001) shows that 1960's decade was one of the most longest and driest period at 'Ladario' station taking account of 95 years of data from 1900. Collinschonn gives a range of 300-400 m³s⁻¹ for mean annual flow and 1100 m³s⁻¹ for mean flood flows in the 'Taquari' river.

The gentle slope of several of the tributaries of the 'Paraguay' river close to their confluence with the 'Paraguay' causes propagation of back water a great distances upstream the confluence. Therefore, the overbank flood discharges of these tributaries depends not only on the discharge coming from upstream but also on the water level in the 'Paraguay' river. Two years observations (UNESCO, 1973) at 'Porto da Manga' showed an yearly average discharge of around 900 m³/s. At the same place, where the 'Paraguay' and 'Taquari' rivers join the flow velocities measurements gave values around 0.86 m/s. Upstream this confluence the flow velocities was only 0.58 m/s.



3. Materials and Methodology

3.1. Materials

3.1.1. Digital Elevation Model (DEM)

The SRTM obtained elevation radar data in high-resolution digital topographic database of the Earth. The single pass SAR interferometry of SRTM gave an interferogram from two channels measure with slightly different ranges R_1 and R_2 for any ground point. From this two-dimensional phase field the DEM of the imaged area could be computed after the 2π ambiguity of the phase measurement was removed by a procedure called phase unwrapping. The data are available in extension '.hgt'. It is not a format type. The meaning of '.hgt' is 'height'. The files are in 'raw' format (without headers and not compressed) with 16-bit signed integers, elevations measured in meters above sea level, in a geographic projection

3.1.2. Satellite images

Three different types of optical images were used it: ASTER, LANDSAT-TM and SAC-C.

- ASTER image mosaic

Acquisition date: 2000 - 2003

Pixel resolution: 15 m

- LANDSAT TM mosaic

Acquisition date: 1998 - 2000

Pixel resolution: 30 m

- SAC-C.

Pixel resolution: 180 m

Date	Spectral channels
08/08/01	1 to 5
04/03/02	1 to 5
28/09/02	1 to 5
24/04/03	1 to 5

Table 4: SAC-C images available.

	Band 1	Band 2	Band 3	Band 4	Band 5
λ (μm)	0.45	0.55	0.65	0.82	1.57

Table 5: Spectral characteristics (λ) of the SAC-C satellite.

The mosaics used from ASTER and LANDSAT TM helped to improve the interpretation of the complex drainage network. Because the DTM is having a 90 m pixel resolution it was necessary to use images with pixel resolution less than 90 m. It was also necessary to use both ASTER and LANDSAT TM because, for example, some small places were covered by clouds which was enough to obstruct identification of streams. On the other hand, in spite of the fact that the ASTER mosaic is better compared to LANDSAT TM mosaic with respect to spatial resolution, sometimes the ASTER mosaic didn't allow to distinguish certain terrain features. In these particular cases, LANDSAT TM mosaic allowed to determine terrain features because its acquisition date was different than the ASTER mosaic.

SAC-C images were used in two different ways. First, a particular image was used to calculate the NDVI map for the 'Pantanal' region. Although the region is very large the SAC-C pixel resolution allows to cover it in only one image. The advantages were a homogeneous features captured and the absence of clouds in the image selected. Secondly, a reclassification of four images from different times allowed to detect the areas that are affected by the flood events. The four different times assisted to distinguish different altitudes with respect to the flooded areas.

3.1.3. Vector

An initial vector file for the drainage network was obtained from EMBRAPA. The vectors were digitized from old topographic maps and partly updated using LANDSAT TM mosaic. The original dataset was not consistent at the boundaries of topographic map sheets and changes in the drainage system (topographic map based on 1960 data) had to be incorporated as well.

3.1.4. Software

- ILWIS Academic 3.2
- Arc View 3.2
- Arc GIS 8.3
- Erdas IMAGINE 8.6

3.1.4.1 ILWIS Academic 3.2

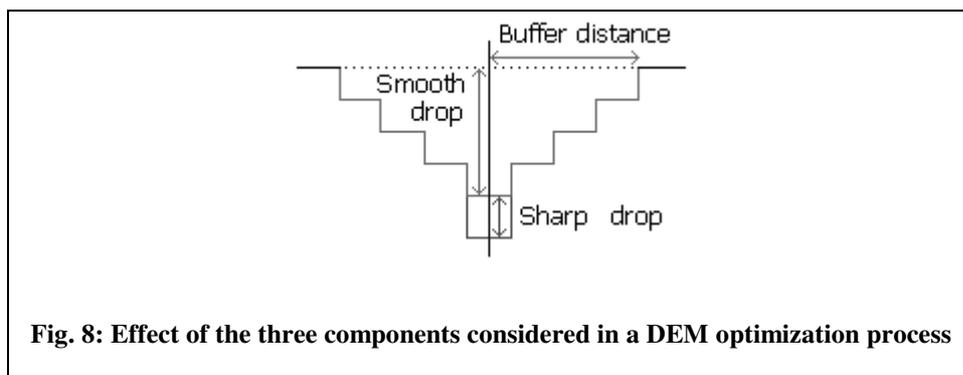
A particular and crucial aspect in this work was the treatment of the drainage network. Because of this it is necessary to explain the main features related to the software that permit this application. ILWIS Academic 3.2 contains a new and special module related to Hydrologic Flow Operations. This process is consisting of four major steps.

3.1.4.1.1 DEM optimization

The DEM optimization process (could be also called bathymetric optimization) can be used to enhance a Digital Elevation Model (DEM), on which it wishes to use the flow direction process later. The DEM optimization process will 'burn' existing drainage features into the DEM integrating the DEM (raster map) and drainage network (vector map). The DEM optimization process is able to (Fig. 8):

- Generate a gradual drop of (drainage) segments in the output DEM, over a certain distance to the (drainage) segments.
- Generate a gradual raise of (watershed-divide) segments on the output DEM, over a certain distance to the (watershed-divide) segments.
- Generate an additional sharp drop or raise of segments on top of the gradual drop or raise.

The result of using the DEM optimization operation is a 'corrected' DEM in which existing drainage features are more pronounced.



The buffer distance determines the width at either side of a segment where height values should be adapted. Smooth drop determines the height with which segments and their surroundings (as specified by the Buffer distance) should be gradually dropped (positive value) or raised (negative value) in the terrain. Sharp drop determines the height with which segments themselves should be dropped (positive value) or raised (negative value) in the terrain.

3.1.4.1.2 Fill sinks

Before using the flow direction process, in a DEM that requires to be used for hydrological modelling is necessary to clean up the DEM from local depressions (sinks) and they should be removed. The Fill Sinks process removes (except pixels at the border of the map):

- depressions that consist of a single pixel, for example, any pixel with a smaller height value than all of its 8 neighbouring pixels. That altitude is increased to the smallest value of its 8 neighbour pixels.
- depressions that consist of multiple pixels, for example, any group of adjacent pixels where the pixels have smaller height values than all pixels that surround such a depression. Those altitudes are increased to the smallest value of a pixel that is both adjacent to the outlet for the depression, and that would discharge into the initial depression. This case is shown in Fig. 9. The lowest pixels in the depression are raised at the same elevation that the pixel in the circle which determines the outlet of the depression.

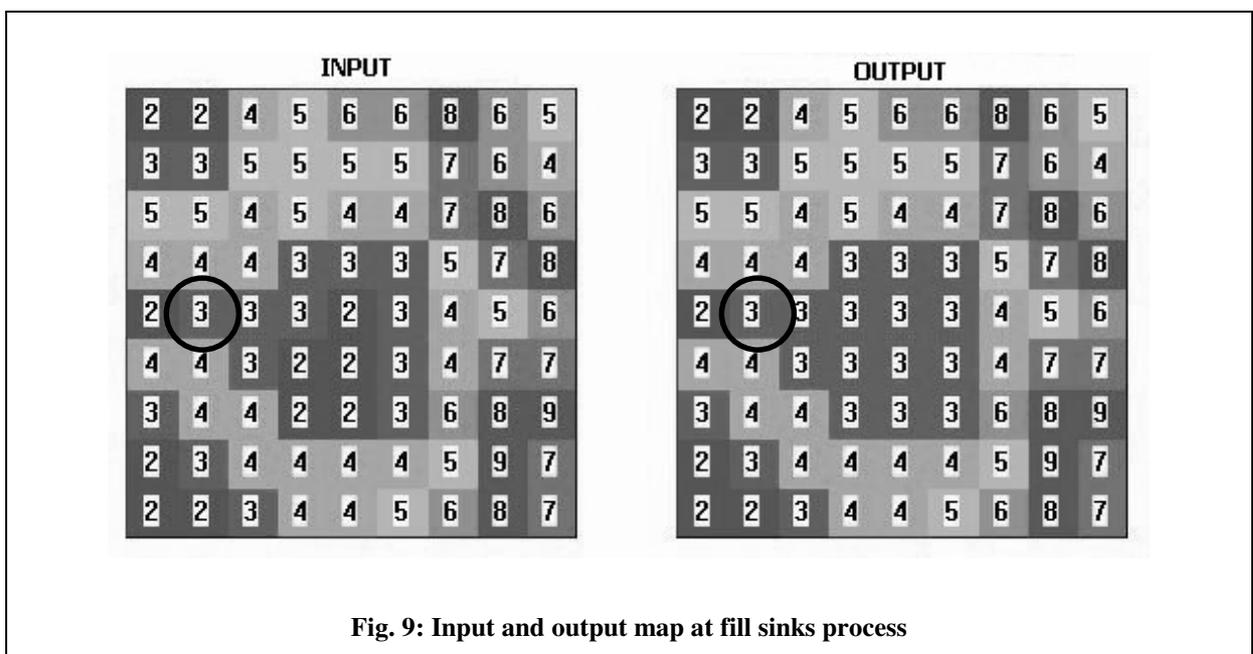


Fig. 9: Input and output map at fill sinks process

3.1.4.1.3 Flow direction

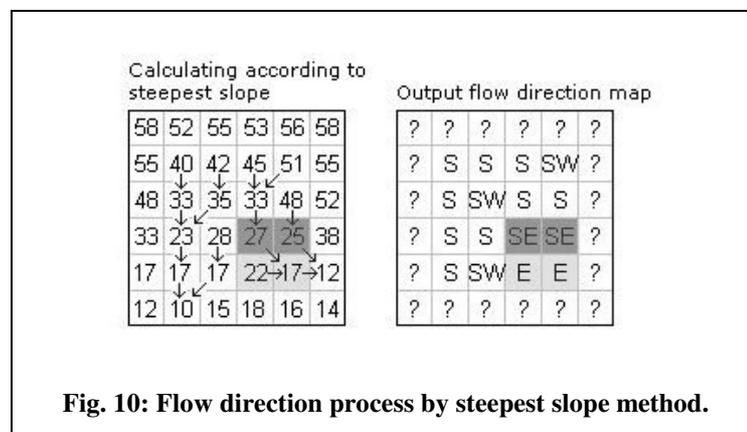
In a (sink-free) DEM, the flow direction process determines into which neighbouring pixel any water in a central pixel will flow naturally.

Flow direction in a DEM is calculated for every central pixel of input blocks of 3 by 3 pixels, each time comparing the value of the central pixel with the value of its 8 neighbours. The output map contains flow directions as N (to the North), NE (to the North East), etc.

It is possible to choose between two ways to do the calculations:

- Steepest slope: find the steepest downhill slope of a central pixel to one of its 8 neighbour pixels. The calculation takes in account the difference in distances between the central pixel positions, for example, in north or in north-east direction. To the corners the height difference values are divided by 1.4 and in the horizontal and vertical neighbours are divided by 1.
- Lowest height: simply find the neighbour pixel that has the smallest value of all 8 neighbours, while this value should also be smaller than the value of the central pixel. In this case the weight assigned to the directions is the same for all directions.

The flow direction process is shown in Fig. 10 using a steepest slope method.



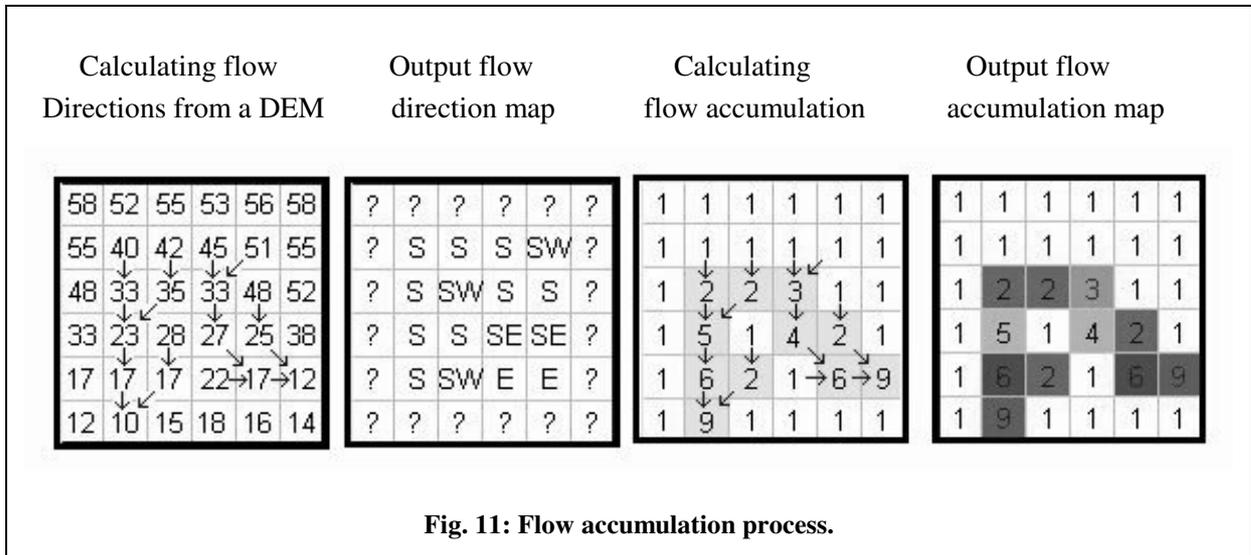
3.1.4.1.4 Flow accumulation

The Flow accumulation operation performs a cumulative count of the number of pixels that naturally drain into output pixels. The operation can be used to find the drainage pattern of a terrain.

As input the operation uses the output map of the flow direction process.

The output map contains cumulative hydrologic flow values that represent the number of input pixels which contribute any water to any output pixel; the outlets of the largest streams, rivers etc. will have the largest values.

The Fig. 11 shows a scheme showing the flow accumulation process.



3.2. Methodology

3.2.1. General description

Based on single pass interferometry by the “Shuttle Radar Topography Mission” (SRTM) in C band (centre wavelength of 5.6 cm) a Digital Surface Model (DSM) was obtained. To know the real height of the terrain, features like vegetation, should be corrected to get a DTM. The entire ‘Pantanal’ region has a height between 80 to 250 m above mean sea level and the vegetation can have an influence of approximately 10 m in the area called ‘Pantanal’ wetlands according to the classification given by Assine (2004). For the ‘Pantanal’ wetlands it is necessary to consider two features of the terrain. First, the drainage network that must be represented carefully over both the alluvial fan and the fluvial plains in the DTM. Second, the depression areas because they are at lower altitudes than the rivers around them. During the wet season, the depressions are inundated through the ‘vazantes’. ILWIS is an important tool to incorporate not only the drainage network into the DEM but also to assess if a pit exists in the streams. The fill sinks process results in a DEM free of pits in the streams and the flow direction process permits to obtain a DEM that flows naturally towards the lowest altitude in the output DEM. The final DEM is hydrological consistent. Therefore, the correct delineation of the drainage network is a critical task in order to obtain a **DEM optimization procedure for Hydrological Modelling**.

The DEM correction takes into account the three main features mentioned above for DEM modification. The features are vegetation, drainage network and flooded areas. As stated before other DEM modification sequences would yield other results. All the possibilities are included in Fig. 12. The implemented sequence was selected based on the discussion given below.

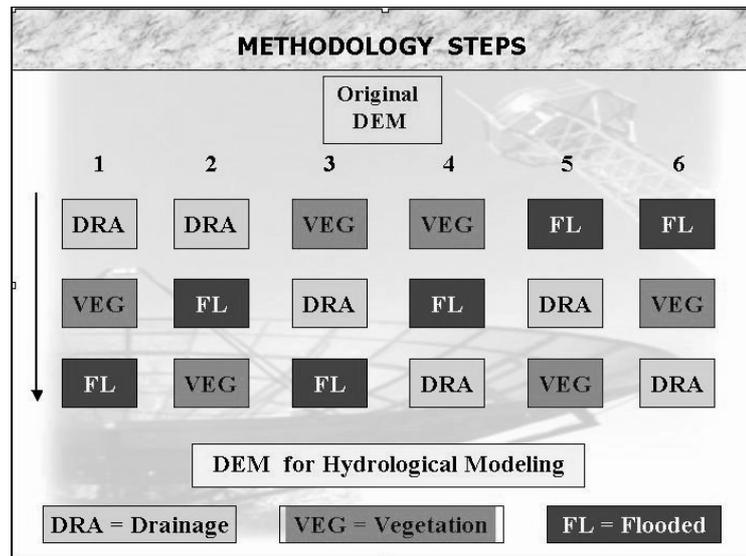


Fig. 12: The six possible ways to apply the improvements into the DEM.

Considering case 1 (Fig. 12), adaptation for drainage network is the first feature incorporated into the DEM. Vegetation and flooded areas are treated after that.

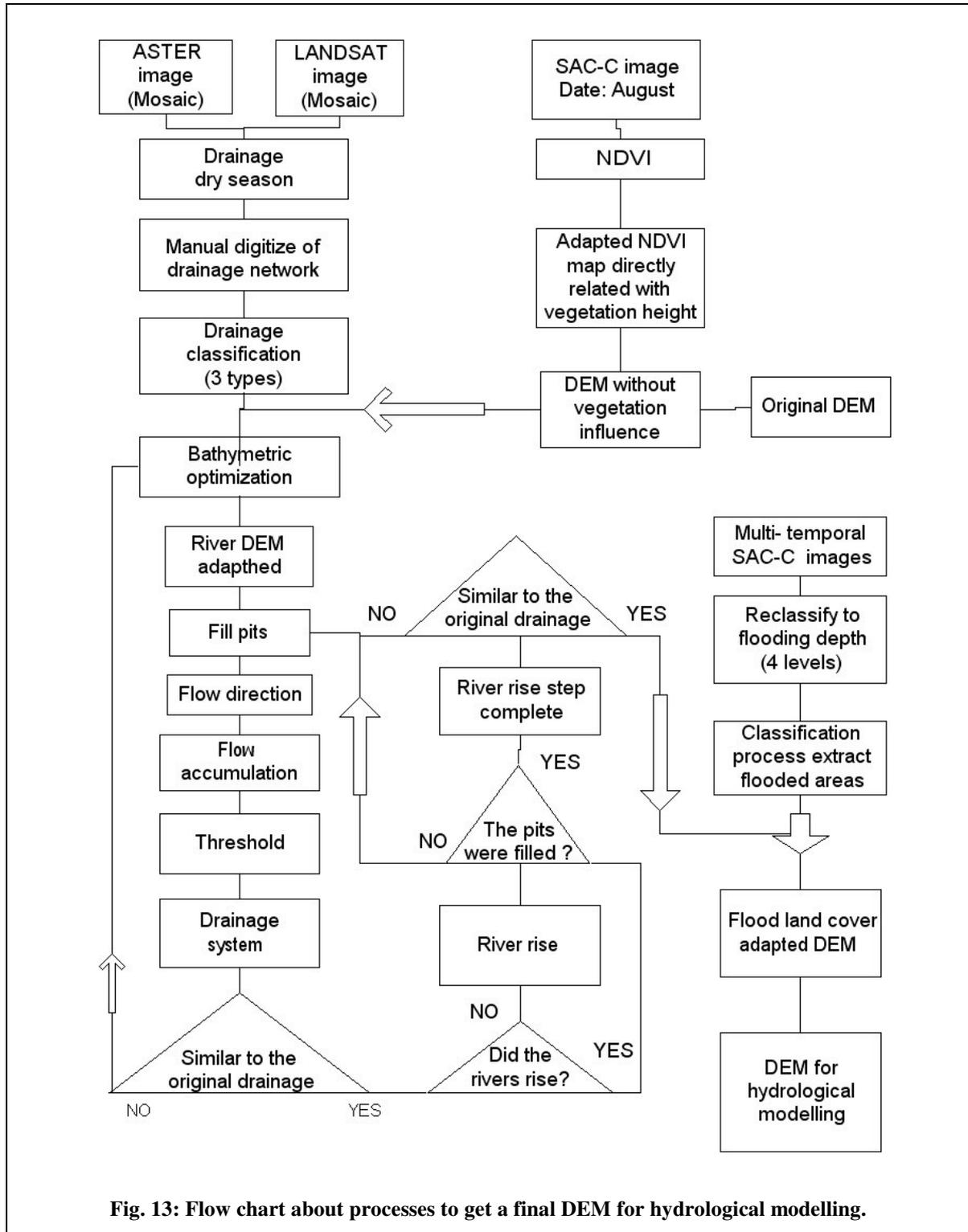
Case 1 and 2 imply to consider bathymetric optimization prior to vegetation correction. Vegetation has a variable height close to the rivers. Vegetation influence is still present into the DEM when bathymetric optimization is considered. Therefore, bathymetric optimization is applied from the top of the canopy close to the river in each place but not from the ground surface. To apply the drainage pull down process in that way would generate uncertainties in the final river depth values. Finally, both cases 1 and 2 were rejected.

Cases 4, 5 and 6 imply to incorporate flooded areas before drainage network pull down. These cases were rejected because of the fill sinks process (belonging to DRA - drainage pull down) which would fill also the depression areas burnt in before the flooded correction process (FL). The result would be losing the flooded area correction.

The assumption is that the correct way to apply the correction sequence is case 3 from Fig. 12. The vegetation influence is first removed. After that, the drainage pull down process is applied knowing the height of the terrain close to the rivers. During the last step the correction for flooded areas is applied.

3.2.2. Flow chart

The steps developed during the research are mentioned briefly in the next figure (Fig. 13)



The next flow chart shows the steps for the flood areas identification process (Fig. 14).

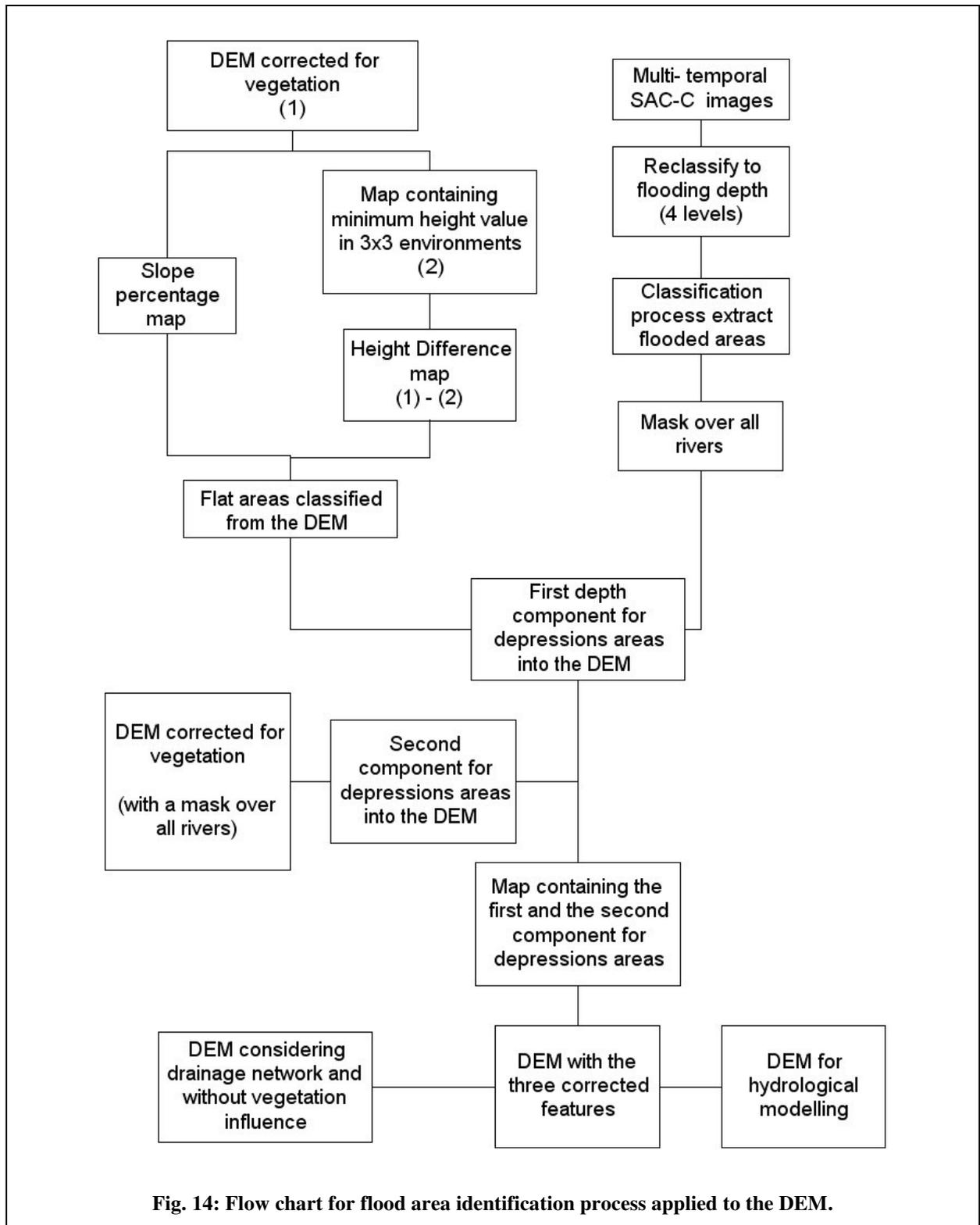


Fig. 14: Flow chart for flood area identification process applied to the DEM.

4. Results and Discussion.

4.1. Classification process to detect vegetation cover

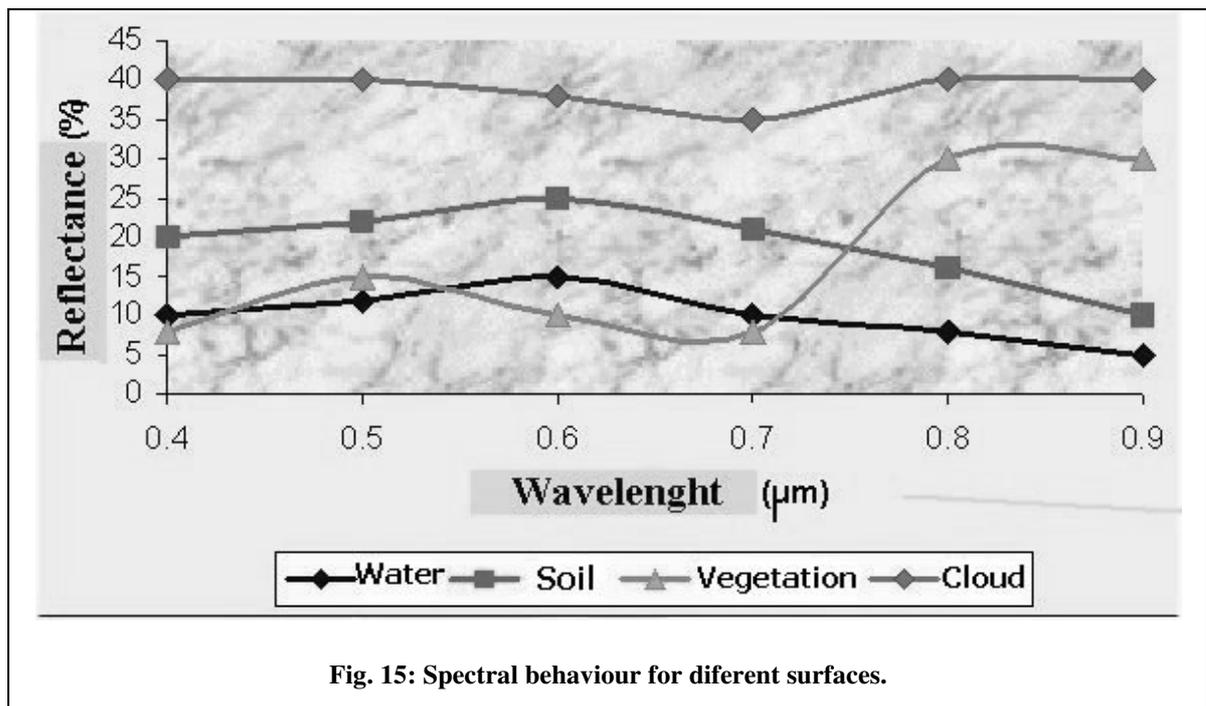
First an unsupervised classification of the LANDSAT TM mosaic was performed in order to correct for the vegetation influence. The unsupervised classification was reclassified for vegetated areas in three different categories. A value in meters was assigned to each category related to the vegetation based on field experiences. The DEM correction obtained was not appropriate. When the DEM was assessed in detail by visual inspection many scattered areas remained with vegetation influence especially near the rivers. Although it is possible to create many classes in an unsupervised classification of LANDSAT TM it is not easy to determine, using a few categories, to assign appropriate height correction values. It would have been possible to create more than the initial 25 classes used trying to get a correct differentiation but the analysis would have been complicated to assign the vegetation height values by these many subdivided categories. Even then it was not sure if a good result would have been obtained using this approach.

Therefore, the SAC-C satellite image was used to calculate the NDVI (Normalized Difference Vegetation Index). The image obtained in August 2001 was used. This image was selected because in August the water levels are low and therefore it is possible to detect vegetation in areas that during the flood season are inundated.

The NDVI determines the 'healthy' vegetation. It takes advantage of the differences exhibited by the vegetation in its spectral behaviour. The pigment in plant leaves, chlorophyll, strongly absorbs visible light (from 0.4 to 0.7 μm) for use in photosynthesis. It is true specially for the ranges 0.4-0.5 μm and 0.6-0.7 μm more than the range 0.5-0.6 μm . The cell structure of the leaves, on the other hand, strongly reflects near-infrared light (from 0.7 to 1.1 μm). Fig. 15 shows the reflectance curves for four different surfaces. The formula (1) is used to calculate NDVI

$$\text{NDVI} = \frac{\text{IR} - \text{R}}{\text{IR} + \text{R}} \quad (1)$$

in which 'IR' means the reflectance value in near-infrared and 'R' means the reflectance value between 0.6 and 0.7 μm (red). The index is higher when the vegetation is in mature state because then difference between 'IR' and 'R' is higher. The NDVI calculated for water, for example, gives negatives values.



The assumption used was that the height of the vegetation could be differentiated based on differences in NDVI values (Fig. 16). The negative values were converted to zero as these represented (open) water bodies. A factor to the index values obtained was applied in order to convert them to represent the vegetation influence. An adapted NDVI map was obtained (Fig. 17). The range observed in this map is between 0 – 11.5 m. Visual inspections looks well representing the whole area and is better compared to the results obtained applying the unsupervised classification based on LANDSAT TM. This assumption related to the vegetation treatment could be further elaborated. Perhaps, an other approach could be applied but the field knowledge available was not sufficient to do so at this stage. However, adapted NDVI map allows to treats well important features such as

- The highest values represent dense forest.
- The values for the levees are in a range of 3 to 10 m.
- The values for the flooded areas are around 2 m.
- No correction for areas totally covered with water was applied.

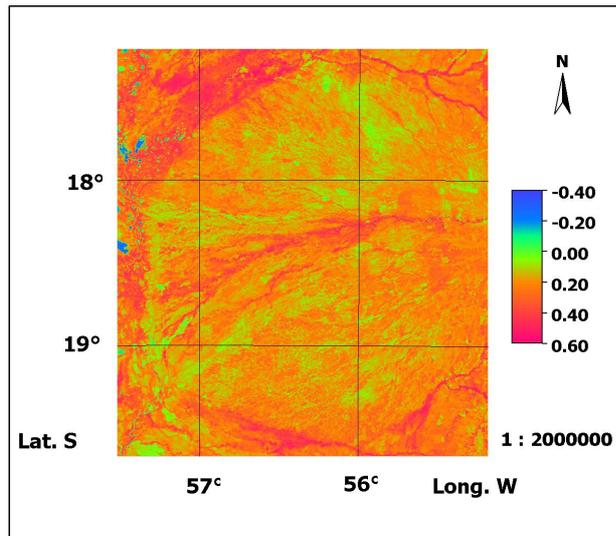


Fig. 16: NDVI map.

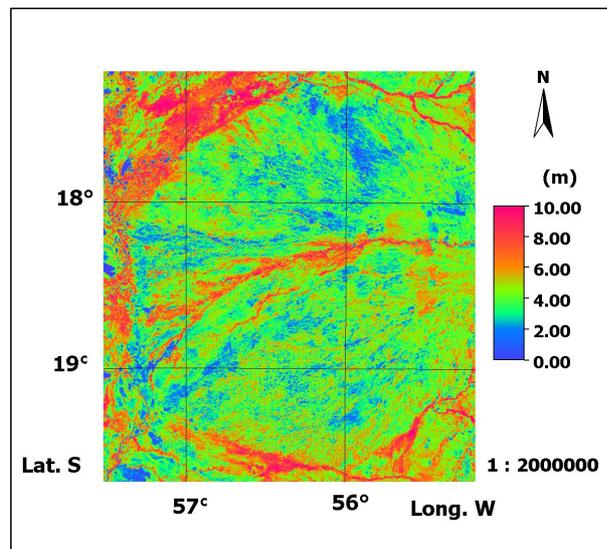


Fig. 17: Adapted NDVI map.

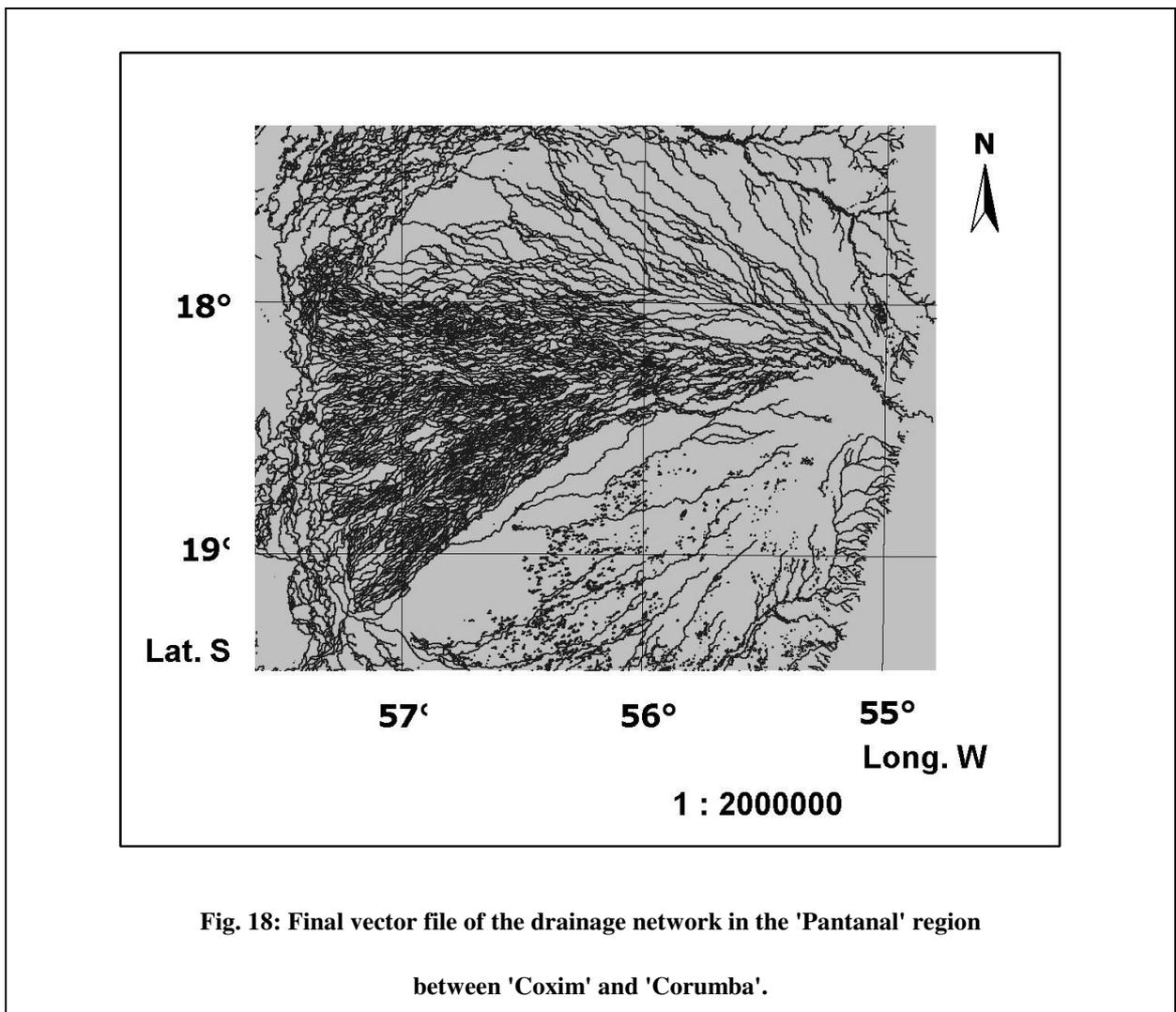
4.2. Dry season period

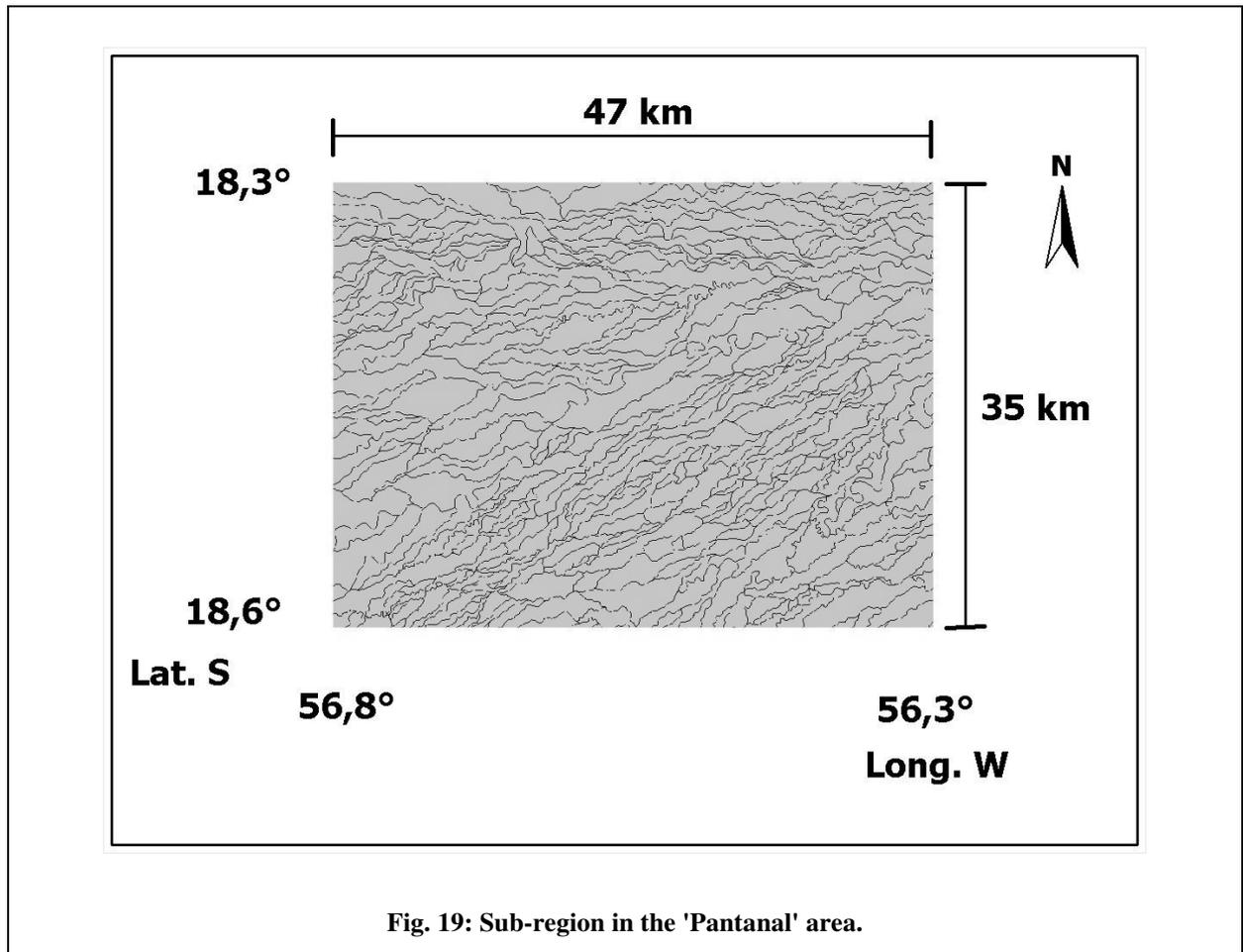
The satellite images (ASTER and LANDSAT TM mosaic) used correspond to the dry season period. It allows to distinguish the state in which the drainage network is nearest to its minimum water

levels because during the flood season the secondary drainage is not visible in the flooded areas. Therefore, selecting these images, the drainage can be visually interpreted.

4.3. Manual digitizing of the drainage network

By manual digitizing the existing drainage network was improved based on recently acquired satellite images of dry season period. Special attention was given to the network connected to the 'Taquari' river (draining into or branching off). Fig. 18 shows the final vector file of the drainage network and Fig. 19 shows the complexity of the network at a larger scale.

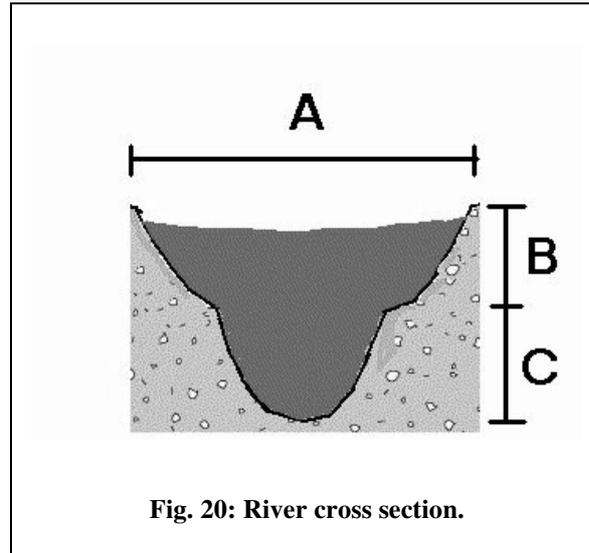




4.4. Drainage classification

The drainage network was classified in three different types of rivers. The 'Paraguay' river vectors were classified in one category; 'Taquari' river vectors were assigned into a second category; all the others rivers of the network were clustered into a third category and were assigned to secondary drainage. This classification considered the main characteristics of the rivers with respect to width and depth.

The Fig. 20 shows the different sections considered for each river that belong to the network.



'A' refers to the total width in meters. 'B' and 'C', refers to the river depth in two sections depending of the river features. Table 6 shows the values assigned for each drainage type.

River	River sections			Total depth (m) (B + C)
	A (m)	B (m)	C (m)	
Paraguay	450*	26	7	33
Taquari	270*	21	7	28
Sec. drainage	90*	3	7	10

Table 6: Width (column A) and depth (columns B and C) associated to each river type

(*DEM has a pixel size = 90 meters).

4.5. Bathymetric optimization

The rivers were integrated into the DEM based on the values shown in Table 6. The DEM bathymetric optimization process was applied in ILWIS Academic 3.2 (2003). This software has a special module recently developed for hydrologic processing and was described before. The first step was to integrate all rivers of the network with the values given for secondary drainage (including 'Taquari' and 'Paraguay' rivers). Next the 'Taquari' and 'Paraguay' were processed in a second step. The result is given in Fig. 21.

The reason why it is necessary to include a process to burn the rivers in the elevation model is because the DSM obtained from SRTM can't distinguish anything below the water surface. The reason is because of the dielectric properties of water the signals does not penetrate into the water body.

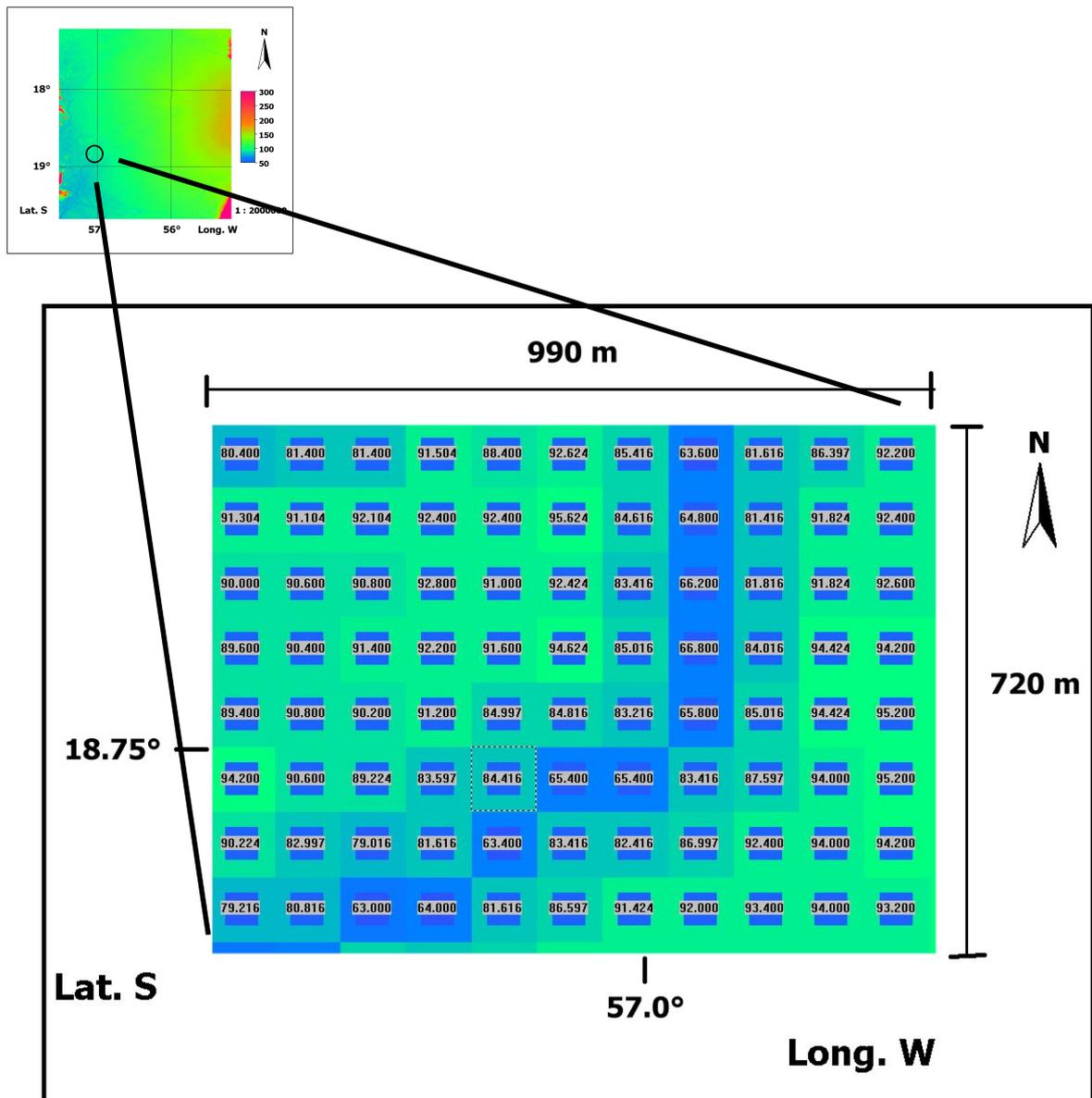


Fig. 21: Detail of the bathymetric optimization process along a section of 'Taquari' river.

4.5.1. Fill sinks

After the DEM optimization process sinks remain. It is necessary to fill the sinks before applying the flow direction operation. Also the fill sinks process was conducted in ILWIS (2003). The process will remove local depressions from the DEM. The details of the process are stated before.

The objective to apply the fill sinks process is to remove pits into the streams. The process ensures that the outlets will always be found towards the edges of the map and lakes flat areas will not act as 'consuming' reservoirs of water but will still discharge towards an outlet. Due to this feature of the process the treatment of flooded areas must be considered after the drainage network. Otherwise, the fill sinks process would have filled up the depression areas as well.

The resulting output map for fill sinks process is shown in Fig. 22.

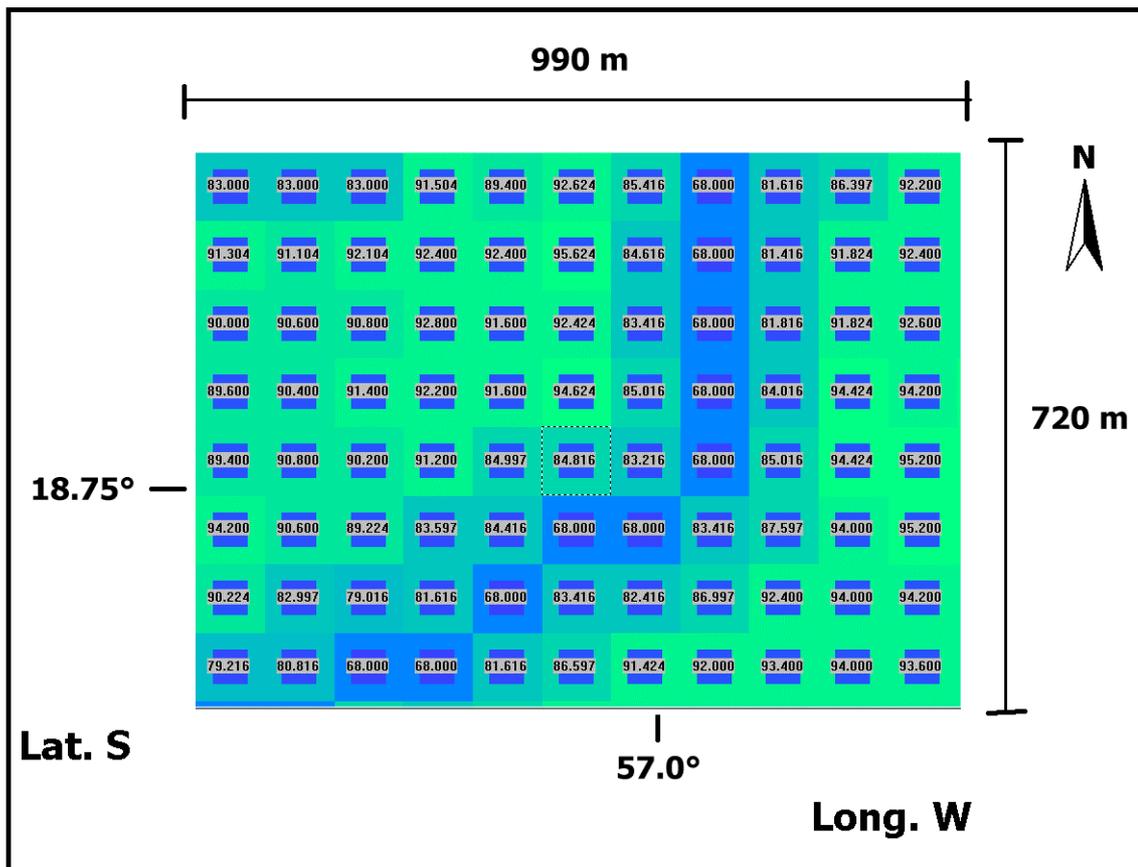


Fig. 22: Detail of the fill sinks process along of the 'Taquari' river (identical to Fig. 19 enlargement)

4.5.2. Flow direction

This process was also conducted in ILWIS (2003). In a DEM free of sinks, the flow direction process determines into which neighbouring pixel any water in a central pixel will flow naturally. Flow direction is calculated for every central pixel of an input blocks consisting on 3 by 3 pixels, each time comparing the value of the central pixel with the value of its 8 neighbours applying the steepest

slope method. This method determines the steepest downhill slope of the central pixel into one of its 8 neighbour pixels. In order to compensate for the distance between the central pixel and its 8 neighbours the height difference values of the 4 corner neighbours are divided by 1.4 and the height difference values of the 2 horizontal neighbours and the 2 vertical neighbours are divided by 1.

The result of the flow direction process is a raster map with all pixels classified in the eight main cardinal directions. Fig. 23 shows the output flow direction map. This step is needed to compute the flow accumulation map.

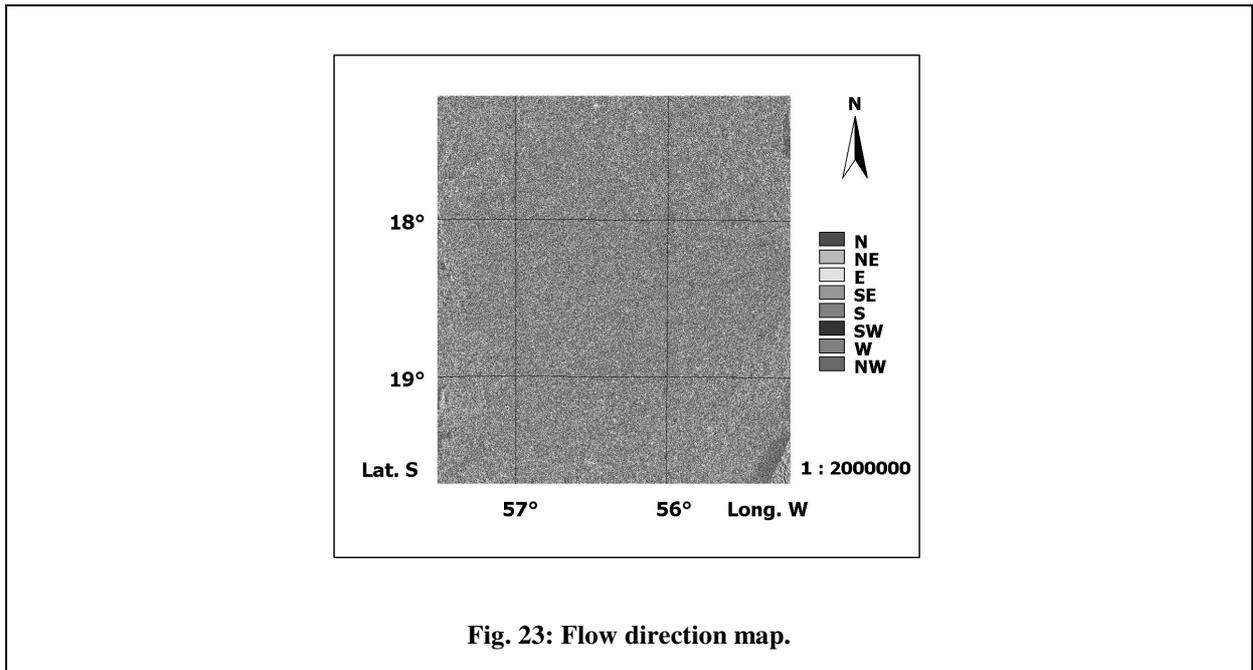
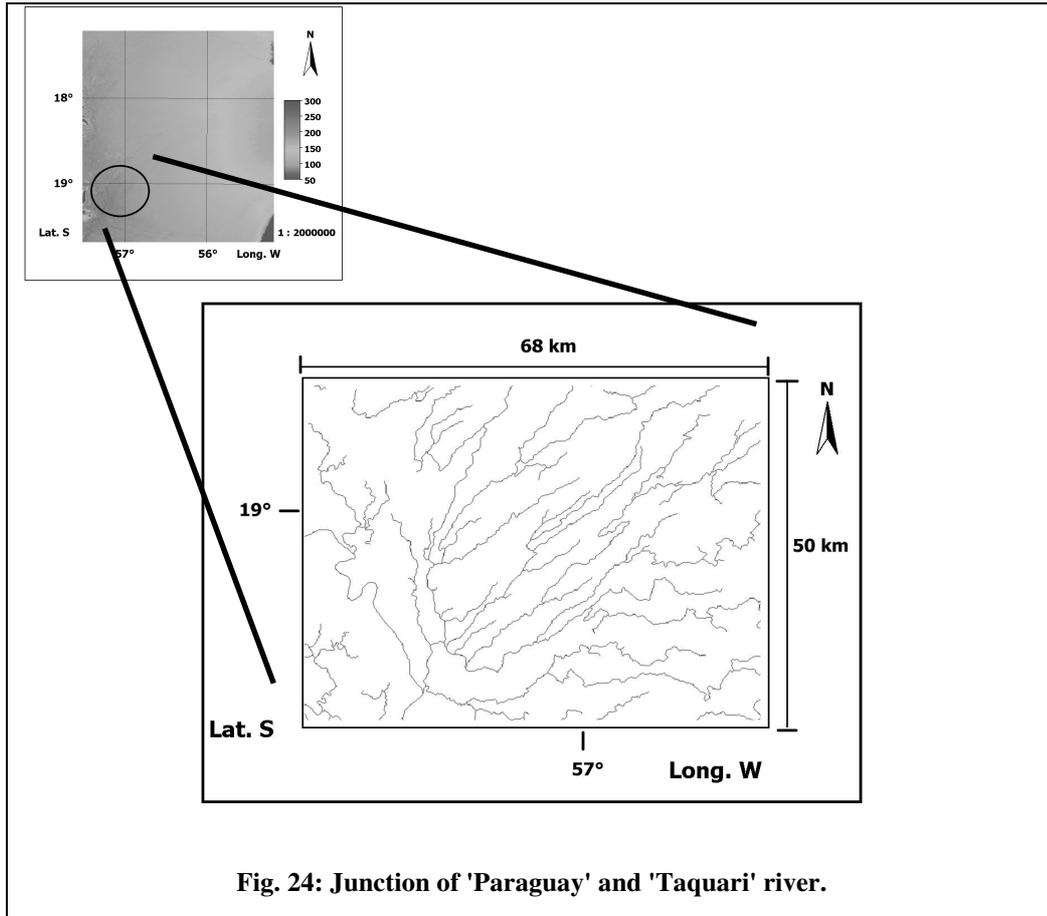


Fig. 23: Flow direction map.

4.5.3. Flow accumulation

Based on the flow direction map, the flow accumulation process performs a cumulative count of the number of pixels that naturally drain into output pixels (ILWIS, 2003). The operation can be used to find the drainage pattern of a terrain. The output map contains cumulative hydrologic flow values that represent the number of input pixels which contribute to any output pixel; the outlets of the largest streams, rivers, etc. will have the largest values. For example, Fig. 24 shows the drainage derived from the flow accumulation map in a sub-region in the 'Pantanal' area. The threshold used was 2000 which is the minimum cumulative count (contributing area) of the number of pixels for which the drainage lines appear in Fig. 24.



4.5.4. Flow accumulation direction check

Due to 'wrong' elevation values at a few locations the flow directions are not properly assigned. Manual correction of some pixels, especially within the drainage, enforces 'correct' flow directions. After an initial check of the flow direction map these anomalies are easily seen by visual inspection and corresponding pixels are adapted. After applying these corrections, as it is possible to see in Fig. 14, the process returns to the fill pits operation. Therefore, the flow direction and flow accumulation (Fig. 25) are re-calculated. The results are again visually inspected and the process is repeated until results are satisfactory.

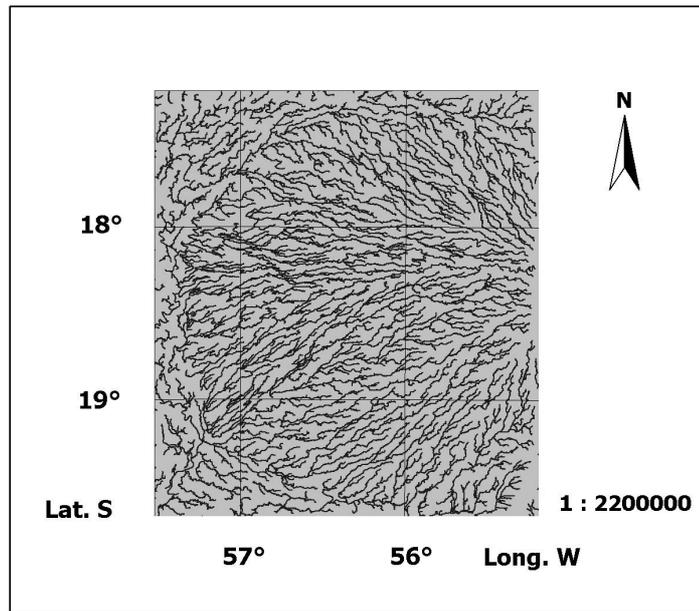


Fig. 25: Flow accumulation map with a threshold of 2000 pixels (16,2 km²)

4.5.5. River rise

To ensure hydrologic consistency the drainage optimization values assigned are not realistic. To get new realistic values the drainage needs to be raised. This process is adopted because there is no control over the fill-pit procedure. Comparing the change after fill-pit with the original DEM shows the influence of the drainage optimization process and fill-pit procedure. These differences can be reclassified to raise the river network.

River depth (m)	Class-value	Class-value*2
(0 - 2]	0	0
(2 - 4]	0.25	0.5
(4 - 6]	0.5	1
(6 - 8]	1	2
(8 - 10]	2	4
(10 - 17]	3	6
(17 - 30]	4	8
> 30	5	10

Table 7: Correction factor applied to the initial pit-filled DTM.

The first column in Table 7 corresponds to the river depth after fill-pit procedure in the DEM. The values in the last column were assigned after a visual inspection in many representatives sectors of the DEM for the three types of rivers. Because of the hydrologic consistency required the exaggerated depths of the streams they are corrected using the last column by which more realistic river depth values in the DEM given field observations that are expected.

The last column in Table 7 is given in meters and was added directly to each river sector (Fig. 26) in the DEM. This process resulted in new sinks in the DEM. The fill sinks process (item 4.5.1) is run again and consequently both flow direction and flow accumulation processes were also recomputed. The result of the flow accumulation process was evaluated again. Fig. 27 shows part of the DEM after the drainage optimization process was completed. Fig. 28 shows the DEM for the 'Pantanal' region.

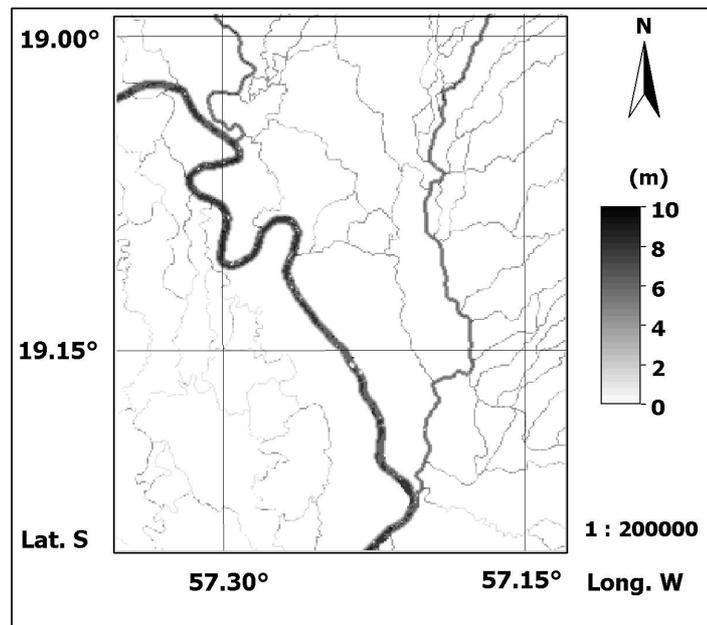


Fig. 26: Raising the drainage. The darker sector corresponds to 'Paraguay' river; the intermediate values belong to the 'Taquir' river; the lighter corresponds to the secondary drainage.

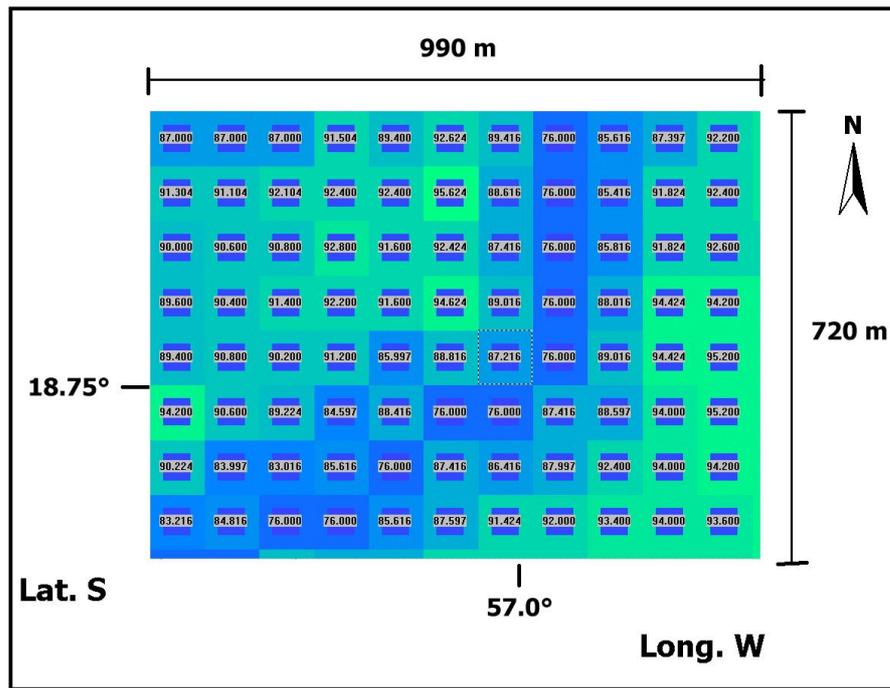


Fig. 27: Example of final results showing the sections of Fig. 19 and 20 along the 'Taquari' sector.

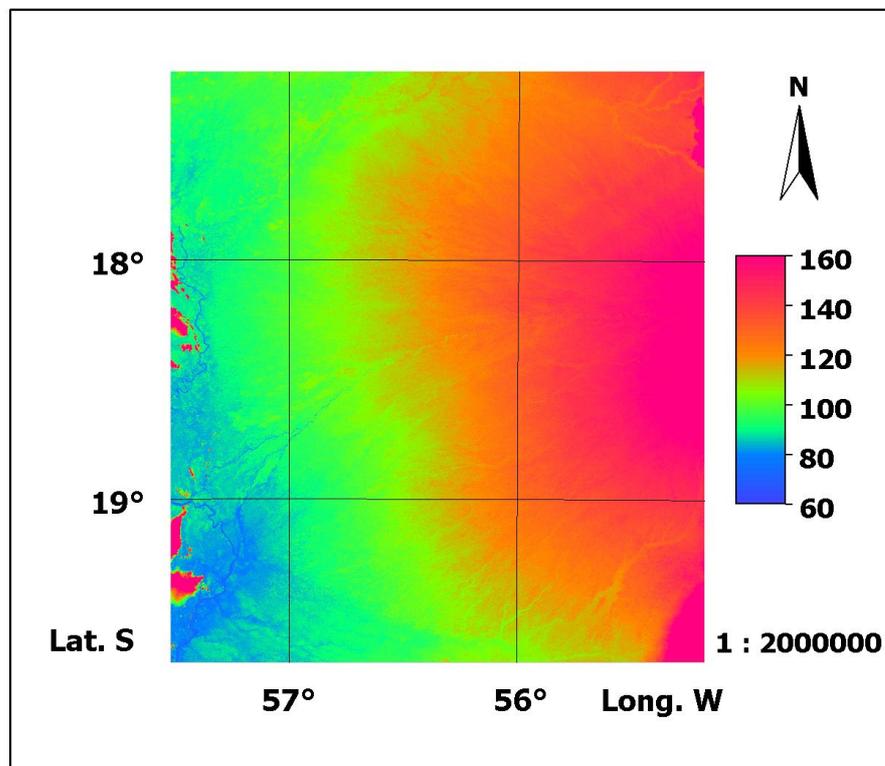


Fig. 28: DEM corrected for vegetation and drainage network.

4.6. Flooded areas

The intermittent flood areas consist of depressions and channels. They become active depending on the height of the flood in each river every year. UNESCO (1973) defines 'vazante' like a drainage line from an area seldom flooded to a 'pantanal' area or to a river downstream. It is a strip of some kilometers wide having a moderate slope in longitudinal direction but without a well-developed channel. When a 'vazante' has a well-defined cross section for a long distance it is called a 'corixoe'. The 'corixoes' would be until three meters below the surrounding surface and after a certain distance they may end in 'vazante' again. In this way, water moves very slowly through the lowland to reach the main rivers.

The correction for flood areas in the DEM tries to incorporate the features described above. The radar signal can't penetrate the water bodies. The SRTM was executed in February 2000 during the middle of the wet season when the area was affected by the flood event. The depressions areas couldn't be properly recorded using SRTM.

Trying to represent the flood areas in the DEM, the total depth to considered for depressions was divided in two components. The first component is based on the time of each sector that remains flooded during the year. The assumption is that the greater depths areas remain longer inundated. For the second component, a function depending on the terrain altitude can be created. The assumption is that the amount of sediments deposited in the lower alluvial fan is greater than the amount of sediments deposited in the upper part. Therefore, with an altitude function it is possible to represent the ponds in the surface because surfaces situated at greater altitudes are burnt in at greater depth compared to surfaces situated at lower altitudes (representing more sediment deposition).

4.6.1. First depth component for depression areas

An important condition is that all flooded areas map exclude the streams. The reason is because in this way it is possible to generate differences between streams and 'corixoes' into the DEM when DEM is corrected for flooded areas

A reclassification for flooded areas was made based on a multi-temporal classification using the four SAC-C images (Table 4). It was possible to classify areas that remained flooded during the whole year or during certain periods. Individual classified images are integrated and those areas that remained flooded during all periods were assigned higher index values than those areas that were flooded only three times or less (Fig. 29).

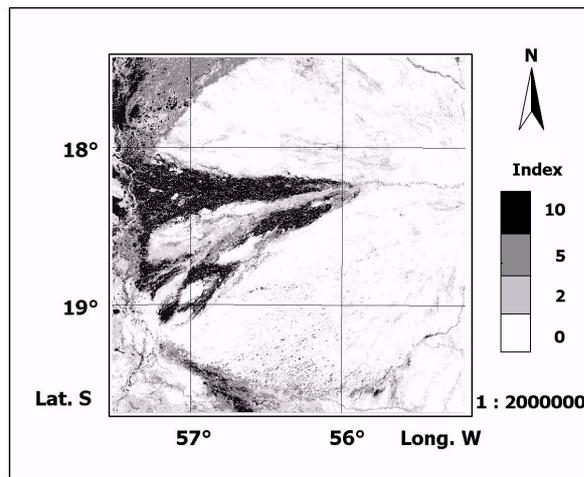


Fig. 29: Index values applied to depressions in flooded areas.

Two maps were created (Fig. 14) from the DEM corrected for vegetation influence. The first one is a slope percentage map. Next a filter was applied on the DEM in a 3 by 3 matrix with the same weight for each pixel. The result is assigned to the pixel allocated at the centre of this matrix. The second map was a minimum value map. In this case the output map returns the minimum value found in a 3 by 3 pixels matrix for the whole DEM. In each matrix the minimum value is assigned to the central pixel. The difference between this minimum value map and the DEM corrected for vegetation influence allows to find areas without changes. The assumption was that areas without change or with very little changes correspond to flat areas. The next step was joining both slope percentage and flat areas map in a new one. The condition for the resultant flat areas map (Fig. 30) was a slope percentage less than 1.5 or flat areas map with height differences less than 1.5 m.

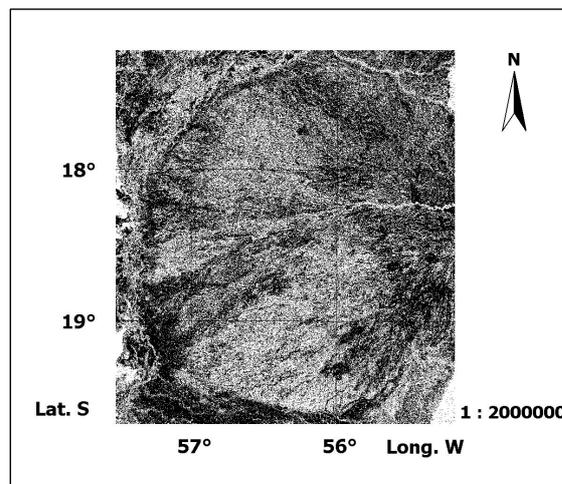


Fig. 30: Dark areas are flat.

The combination between flat areas detected from the DEM (Fig. 30) with the reclassification made for flooded areas based on the multi-temporal classification from SAC-C images (Fig. 29) allows to assign the first depth component for depressions related to flooded areas. The index values from Fig. 29 were converted in meters. Then the values range was 0 – 2.5 m and it was applied for every pixel classified flat in the DEM. Values zero were assigned for both the streams and sloping pixels.

4.6.2. Second depth component for depression areas

The second component for flood affected area correction takes into account the absolute terrain height. A scheme about the depressions is shown in Fig. 31. The DEM corrected for vegetation influence has a certain height value in 'B' slightly higher than the height value in 'A'. To reach the same height value for both 'A' and 'B' at the bottom of the depression implies a different pull down value for each point. Therefore the second component was extracted based on a certain percentage of the elevation in the DEM. The flood correction needs to have values until a maximum of 4 meters. The first component explained before gives maximum values of 2.5 m. Therefore this second component must be in a range of 1.5 – 2.5 meters. The altitude in the DEM varies over 'Pantanal' wetlands between 80 and 180 m but in flood areas the range is between 80 and 140 m. However, the predominant flood areas are situated between 80 and 110 m. Taking 2 % of these values it is possible to obtain the second component. Like the first component, the streams were not considered because it will affect to get the differences between streams and depression areas.

Thus, the final flood correction factor applied with the two components is shown in Fig. 32.

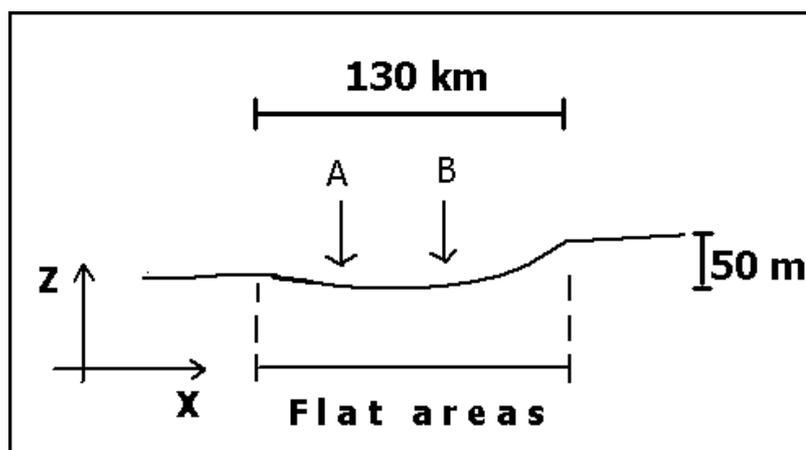


Fig. 31: A depression scheme in flat areas. Depressions normally cover areas between 0.3 and 1 km².

(The scheme is not in scale).

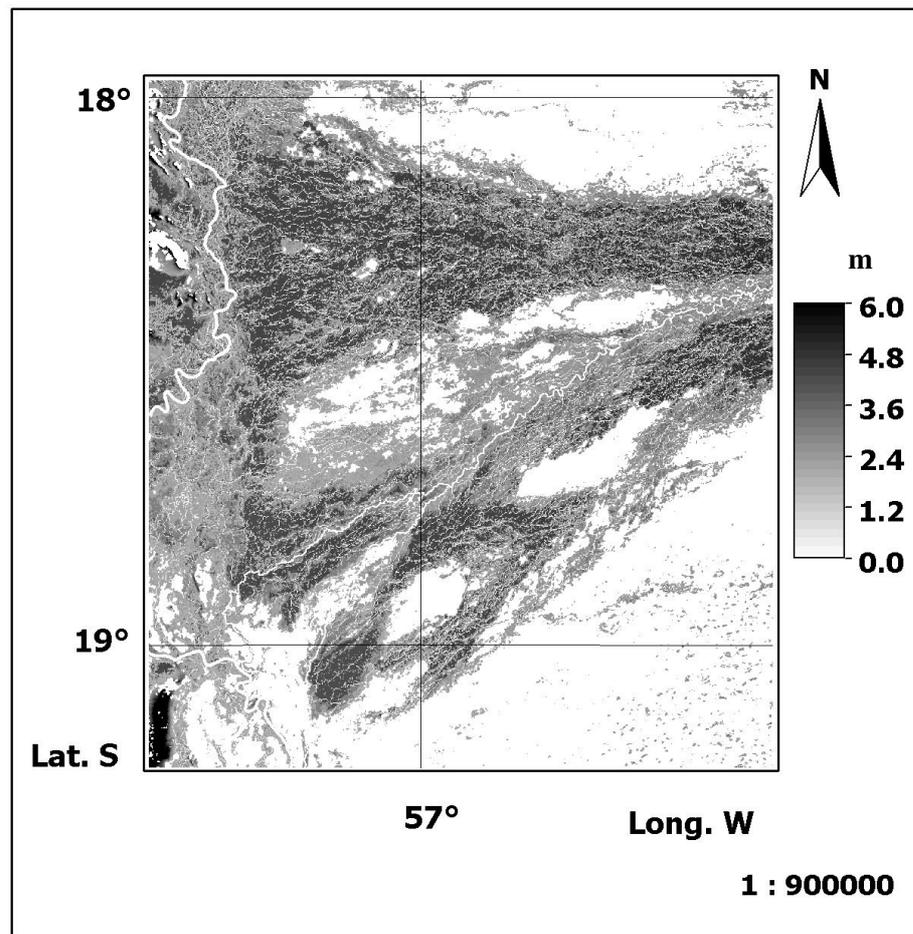
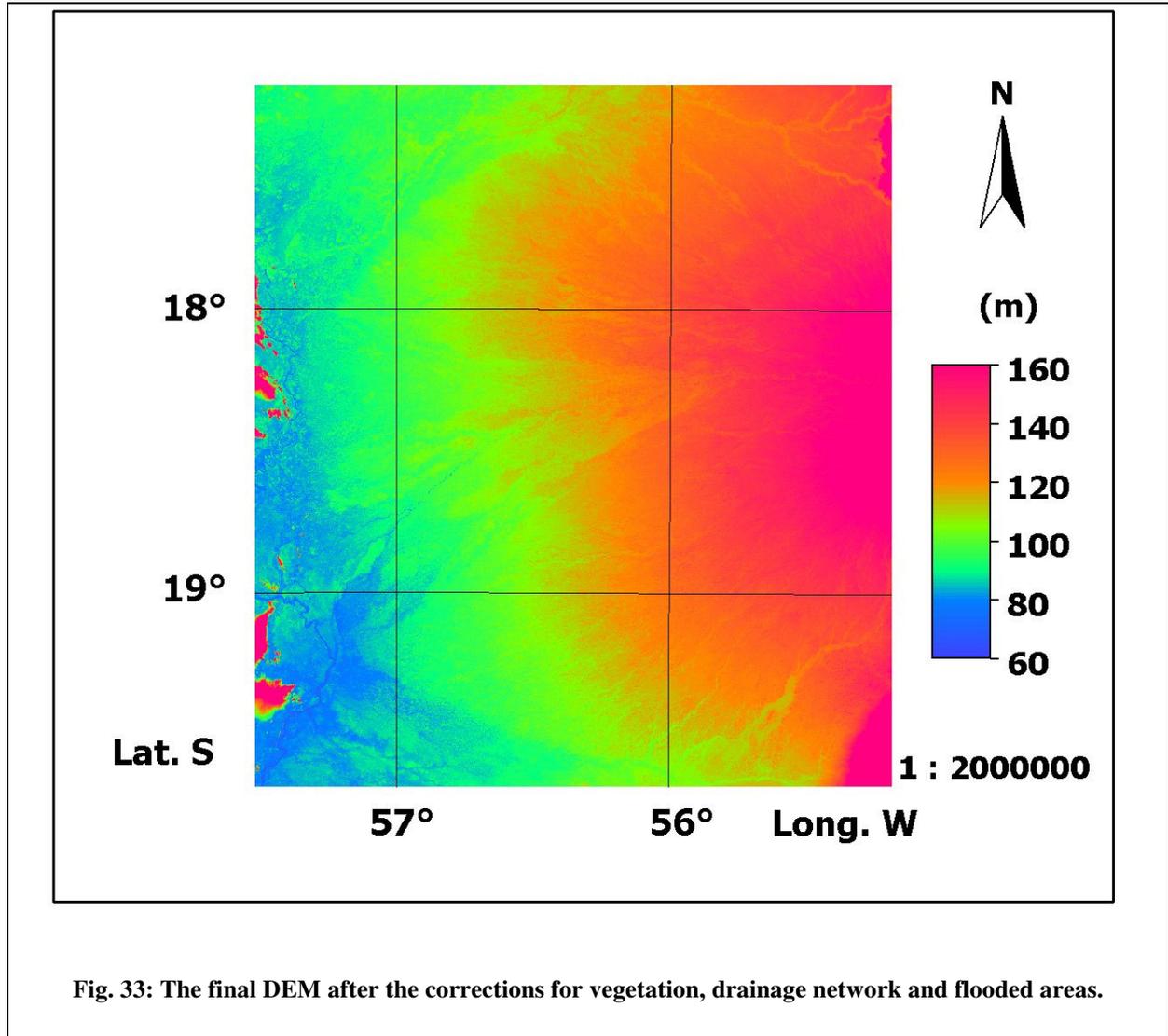


Fig. 32: Final flood area correction map.

The last step applied is the subtraction of the values of Fig. 32 for the DEM corrected for vegetation and drainage network (Fig. 28). Fig. 33 shows the final DEM obtained after applying all correction factors.



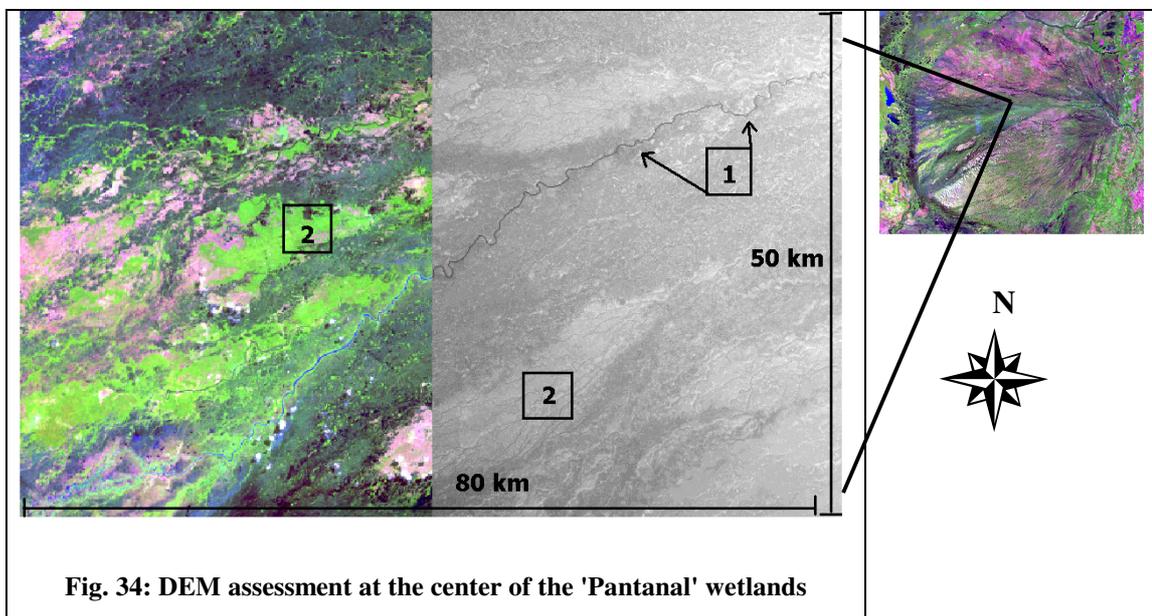
5. Final discussion

5.1. Assessment between the DEM and satellite images

The comparison between the DEM and satellite images is a qualitative method to assess the DEM optimization process. In all figures showed here, the gray scale corresponds to the DEM and the color portion corresponds to a of these recent LANDSAT TM mosaic (showed by an approximation of the natural colors). The assessment was made in many places in the 'Pantanal' wetlands. Some representative places are shown and analysed in the discussion below.

5.2. General aspects

Fig. 34 shows an area that starts a few kilometres downstream of 'San Goncalo' (along the 'Taquari' river) at the beginning of the alluvial fan.



The 'Taquari' river is well represented (1). The altitude at the bottom of the river varies between 8 to 13 meters with respect to its borders. The bottom altitude of the river changes very slowly in downstream direction. It is a good representation in the entire stream but there are also four points at the last portion of the upper fan (out of image, upstream in Fig. 34), where the bottom jump between 2 and 5 meters in contiguous pixels. These points must be corrected by manual adaptations.

In spite of this wrong approximation, the derived drainage obtained was not affected. The secondary drainage looks well in Fig. 34. It is possible to distinguish the levees at the margins for both 'Taquari' river and secondary drainage with variable height between 1 and 4 meters. The higher sectors in Fig. 34 (2) are also well represented. The altitude differences reach between 8 to 12 m with respect to surrounding areas.

Fig. 35 shows the drainage derived from the flow accumulation map for the same area showed in Fig. 34. The threshold use was 2.000 which is the minimum cumulative count (contributing area) of the number of pixels for which the drainage lines appear. The line drawn between A and B, refers to the cross-section shown in Fig. 36. This cross-section corresponds to a representative sector of the 'Taquari river' in the DEM. It is possible to see the effect of the burn drainage process.

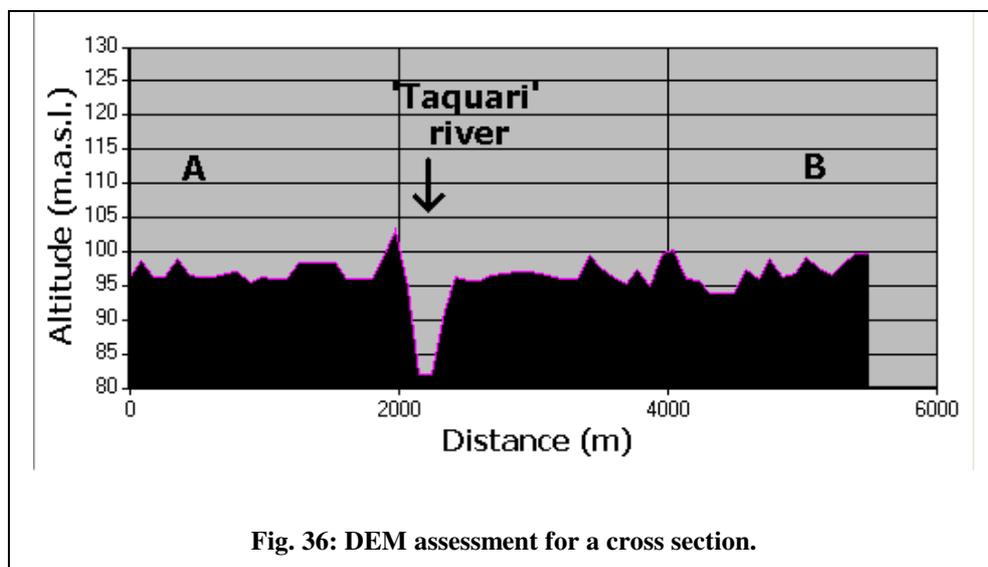
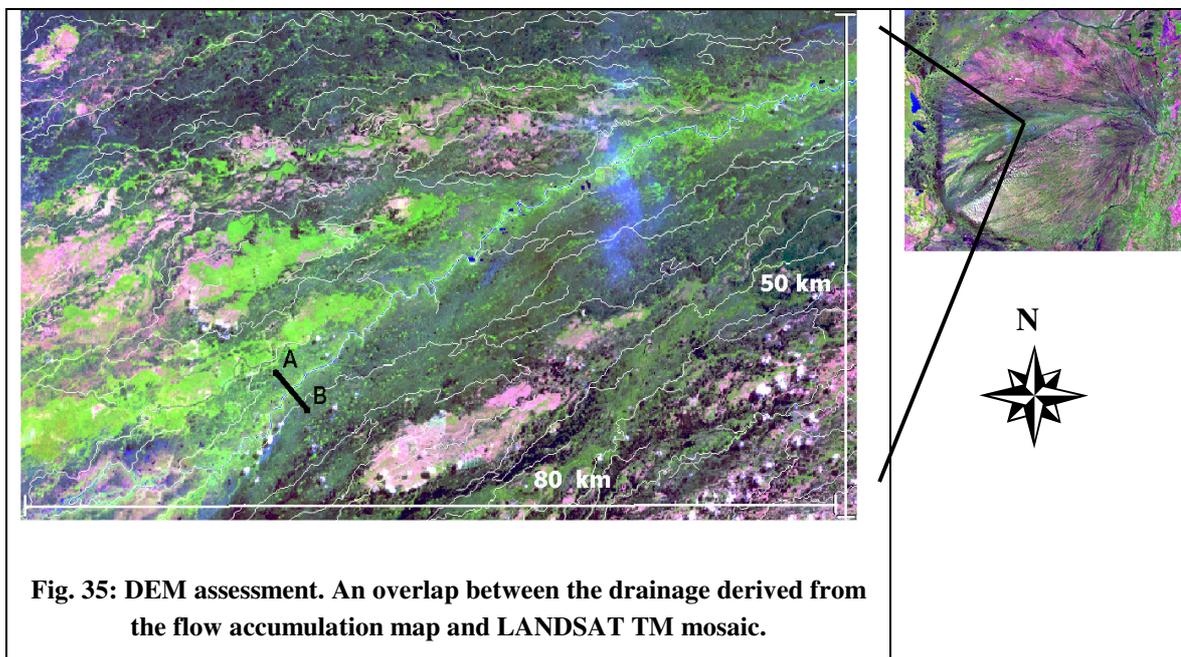


Fig. 37 shows an example of a portion along the 'Taquari' river at Porto Rolon. The comments about the features for this image are similar to the comments made for the image in Fig. 34. The main intention with Fig. 37 is shows the features in a different scale than Fig. 34.

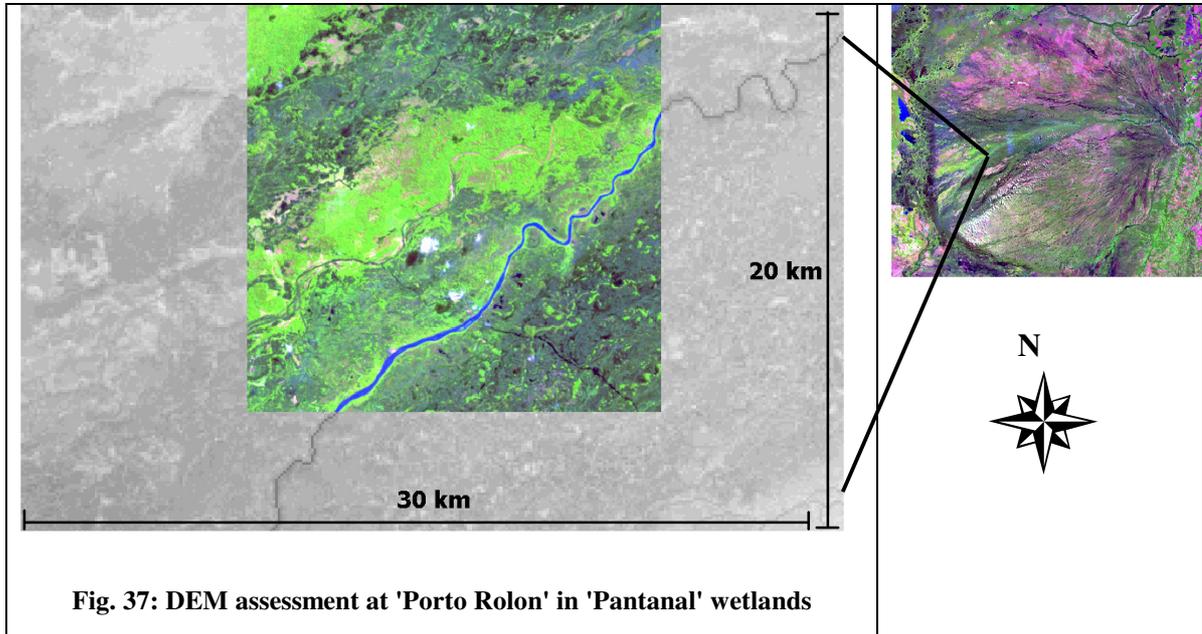
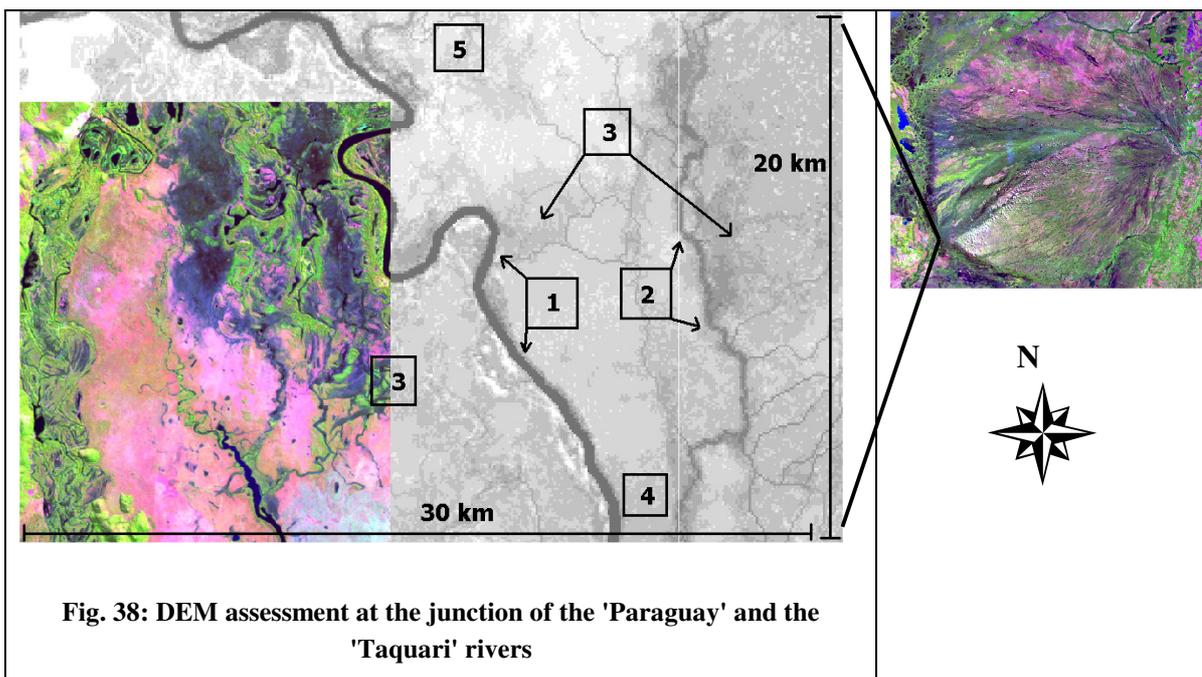


Fig. 38 shows a sector of the 'Paraguay' river (1) in the fluvial plains, near the junction with the 'Taquari' river (2). The marshy areas are well represented in the fluvial plains (3) and they can be recognized not only in the colour part of the image but also in the gray scale in the DEM. It is possible to distinguish marshy areas with dark tones in the DEM close to both the 'Paraguay' and the 'Taquari' river. Marshy areas have tones slightly lighter than the tones in the rivers.



Also in Fig. 38, the elevations at the junction of the 'Paraguay' and the 'Taquari' river are in average close to 82 meters (4) and the elevations in the north part of the DEM are in average close to 85 meters (5). This is consistent with the reality. Fig. 39 shows a cross-section between sectors (5) and (4) from Fig. 38.

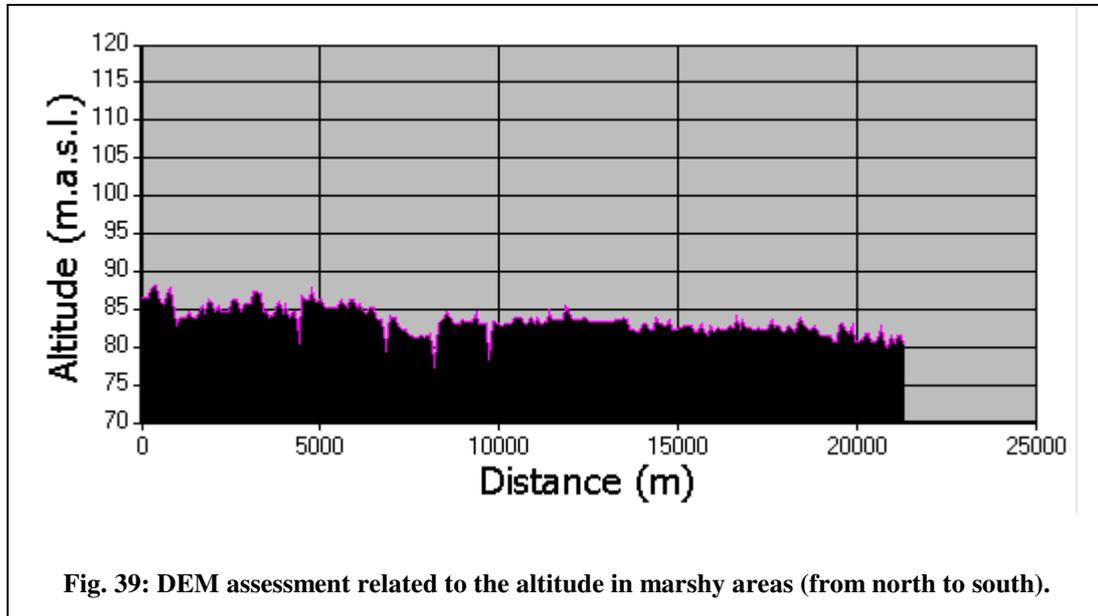
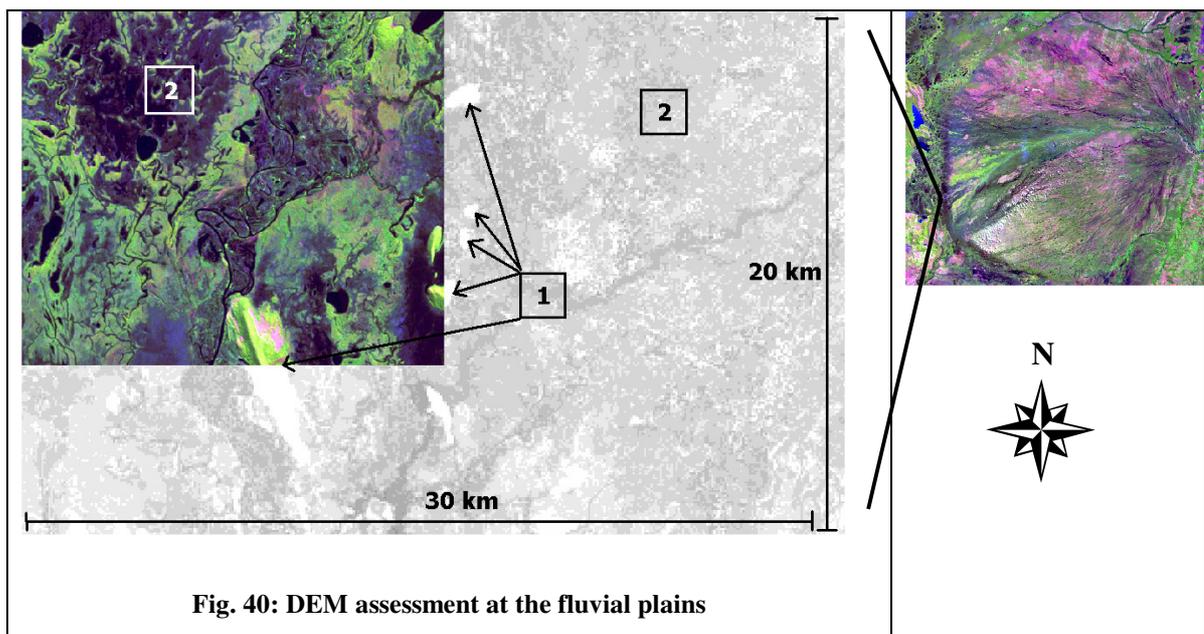


Fig. 40 shows a sector in the fluvial plains, north of the junction of the 'Paraguay' and the 'Taquari' rivers. It is possible to recognize the hills (1) which reach an elevation between 200 and 230 meters. The hills are represented very well for both the position and the elevation in the DEM. Also the marshy areas (2) are well represented.



6. Conclusions

It was possible to optimize a DEM (Digital Elevation Model) for Hydrological Modelling based on a DSM (Digital Surface Model) obtained from SRTM (Shuttle Radar Topographic Mission).

The three main features at the terrain in 'Pantanal' wetlands were considered in the optimization process: vegetation, drainage network and flooded areas. All of them could be represented in the final DEM.

The corrections for the three main terrain features in 'Pantanal' wetlands must be applied in a determined order. Therefore, the correct way to apply the correction sequence is,

- the vegetation influence is first removed.
- the drainage pull down process is applied in second term.
- the correction for flooded areas is the last one.

A detailed visual assessed of the DEM compared with the satellite images (ASTER and LANDSAT TM) allowed to conclude that the obtained DEM is a realistic representation of the complex characteristics of the terrain in the 'Pantanal' wetlands.

The 'Pantanal' wetland has an extensive and complex drainage network in a terrain with very gentle relief. After incorporation of the drainage in the DEM the representation of the drainage network looks very well when it is compared with satellite images (ASTER and LANDSAT TM). The derived drainage obtained also represents well the flow in the streams towards the outlet in the DEM in a realistic way.

The flood areas correction was necessary because the SRTM obtained data during the middle of the wet season (February 2000). In the flood areas the differences in altitudes at neighbours places reaches an average of 3 meters between main streams and 'corixoes'. The final DEM represents well these differences.

The vegetation correction was applied based on an NDVI map for the whole area. In spite of the method applied here the correction could be improved, but the final DEM seems to represent well the main features related to the vegetation correction,

- The highest values represent dense forest.
- The values for the levees are within a range of 3 to 10 m.
- The values for the flooded areas are around 2 m.
- No correction for areas totally covered with water was applied.

ILWIS (2003) contains a new and special module related to Hydrologic Flow Operations. This software was crucial to fulfil the objectives of this research.

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List for abbreviations

ASTER,	Advanced Spaceborne Thermal Emission and Reflection Radiometer
EMBRAPA,	Empresa Brasileira de Pesquisa Agropecuaria
DEM,	Digital Elevation Model
DSM,	Digital Surface Model
DTM,	Digital Terrain Model
GPS,	Global Positioning System
NDVI,	Normalized Difference Vegetation Index
SAR,	Synthetic Aperture Radar
SRTM,	Shuttle Radar Topography Mission