Pantanal-Taquari: Tools for decision making in Integrated Water Management

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Alterra-rapport 1295

Alterra, Wageningen, 2006

ABSTRACT

R.H.G. Jongman (Ed) 2006. *Pantanal-Taquari, Tools for decision making in Integrated Water Management.* Alterra Wageningen UR, Rapport nr.1295, 215 pag. 156 fig.; 26 tab.; 73 ref.

At present the Taquari is an unstable braiding system with a more or less permanent inundation of 5.000 to 8.000 km^2 in the subregion Paiaguas in stead of periodic inundation belonging to wet savannahs. The result is a decline of the fish populations and a decline of the area for cattle breeding. This project analysed the development of the flooding of the Taquarí in the Pantanal in recent time, scenarios of its impact on land use and biodiversity at present and in the future by developing a digital elevation model, analysing its geomorphological history, its water flows habitat development. Socio-economic aspects have been included only marginally because of the lack of consistent data. Stakeholder meetings have been held during different phases of the project to include ideas and knowledge from the region and to discuss the results with the region.

Keywords: Taquarí, Pantanal, Wetlands, Digital Elevation Model, Inundation, Savannas, Scenario, Biodiversity

ISSN 1566-7197

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Contents

Preface

This report is a draft of the final report of the Pantanal-Taquari project that has been carried out in the framework of Partners for Water under Project number 02.045. It has been a cooperation project between Dutch institutes and EMBRAPA Pantanal. It serves as one of the pilot projects of the Dutch involvement in the World Water Forum. The products and information of this report are an extension of the following projects: “Avaliação das imagens da câmara MMRS no estudo da dinâmica da deposição de sedimentos e do regime de inundação do leque aluvial do rio Taquari no Pantanal: Monitoramento hidrossedimentológico”, approved by CONAE da Argentina, which provided the images of the sensor MMRS, satellite SAC-C and the project “Avaliação da dinâmica de inundação para o gerenciamento dos recursos naturais do leque aluvial do rio Taquari através de geoprocessamento”, supported by FUNDECT.

The authors of this report thank all those who contributed to this project especially Dr Mario Dantas, who draw the attention on the problem of the Taquari, Antonio R. Ioris and Jörgen Leeuwestein both working for the Programa Pantanal when the project was in preparation and in its first phase and who supported us strongly in the important contact with the authorities in Brasilia, Campo Grande and Cuiabá. We also thank all those who helped us without being mentioned in the institute of EMBRAPA but especially all the people, farmers and local authorities and NGOs in the Pantanal who are strongly involved in the problems of the Taquari and are impacted by the present situation. This project has been made possible through funding of the Dutch Programme Partners for Water, Project Number 02.045.

We thank the Embrapa-Pantanal staff and the students for the collaboration. Important data were collected during a field survey on the Taquari in March-April 2004. We would like to thank our excellent ‘boatsmen’ Isaac and Valdomiro (EMBRAPA-Pantanal). Grain size analyses of sediment samples collected in the field were carried out at the soil laboratory of EMBRAPA-Pantanal (Corumbá). Radiocarbon age determinations were carried out at the Robert J. van de Graaff Laboratory (Utrecht, The Netherlands) under supervision of Dr. Klaas van der Borg, who also calibrated the ‘modern’ radiocarbon ages.

For the field survey use was made of sounding and DGPS equipment. The method for quick bathymetric surveys using portable sounder linked to GPS and integration with GIS was developed by Mr. Ing. Remco Dost from the Department of Water Resources, ITC. The dual frequency GPS used was provided by Drs. Klaas Verwer, Department of Sedimentology, Free University of Amsterdam.

Furthermore we would like to express our thanks to Roberto de Ruyver MSc from Argentina who was instrumental in developing the appropriate correction procedures for hydro-DEM optimization. We are also grateful to the ILWIS development team

at ITC for their effort in programming the necessary routines and algorithms needed for DEM hydro-processing.

The final report will be produced in January 2005 and be available in March in print and through the web in both English and Portuguese.

On behalf of the whole Pantanal Taquari team

Rob Jongman
Wageningen 14-1-2005

Summary

In the 1970s the Planalto, the highlands around the Pantanal – a savannah wetland of 320.000 km^2, have been colonised. Until then the Planalto was covered by dry open bush (cerrado). The soil is highly erosive and the colonisation has taken place without consideration of the impact on the Pantanal, one of the world's most important biodiversity areas.

The Pantanal in Brazil consists of a number of large rivers in a joint wetland area. The economy is based on cattle breeding, fishing and ecotourism. Large areas are dominated by the river regime of the Paraguay and its tributaries. In the wet season large areas of the savannah are flooded. Now erosion and silting up make the Taquari into an unstable braiding system. This is at the moment a major problem causing in an area of 11.000 km^2 a more or less permanent inundation of 5.000 to 8.000 km^2 in the subregion Paiaguas in stead of periodic inundation. The result is a decline of the fish populations and a decline of the area for cattle breeding.

The main conclusions of the project are:

- Putting science into context: The important added value of the project is that knowledge has been set into context of the river as an ecosystem and a socio-economic unit. Within that context the links between science fields (hydrology, ecology and economics) have been made.
- Biodiversity can be important for regional economy: Less aquatic biodiversity means less fish, less fishing tourism, less ecotourism, less income and more isolation. The relationship of the hydrological behaviour of a river system and its ecological functioning (the flood pulse) can also be an important lesson to be learned for river management in Europe.
- The role of stakeholders and capacity building: In a situation where politics is important, it is essential that all are involved and discuss matters using political and scientific arguments and the right economic and hydrological models to explain the situation. Proper knowledge appeared the only convincing argument for taking decisions.
- Organisation of water management: It is important that the results of the project will be accepted both in the region and by authorities that supervise the region.
- Technical solutions are not always the best solutions: Technical solutions such as building a dam have been proposed by different stakeholders and the project was capable of showing the consequences, both positive and negative.
- Research coordination and cooperation: An important aspect that has been learned is that the cooperation between and the coordination of policy and research can be improved considerably; both can benefit from this.

In general, understanding the hydrological dynamics and related ecology of rivers at the basin scale and communicating this with the organisations and people involved is the basis of economically and ecologically sustainable river management

1 The context of the problem

Rob Jongman[1], Carlos Roberto Padovani[2] and Mário Luiz Assine[3]

1.1 Objectives of the Project

The objective of this Partners for Water (PvW) project is: "Support the wise use of the plains of the Pantanal Taquari river basin, focussing on the tools for policy decision-making in river management".

The project is a pilot and demonstration project to assess the consequences of river management and related land use in one of the catchments of the Pantanal, the Taquari River. It has been focussing on the downstream ecosystems and land use and supports the development of an organisational model for management of the river basin, in co-operation with and supported by farmers, nature conservation representatives and national and state authorities. This is worked out in five strategic objectives:
Development and use of a "goal oriented" dynamic approach of modelling of the catchment on land use and the river behaviour, using existing data and knowledge provided by the relevant actors (Federal and State Governments, Municipalities, NGO's, farmers and other private and public interest groups) and the Dutch partners;
Inventory of gaps in knowledge and definition of the research and development agenda;
Facilitation of the policy decision-making process by providing insight in possible scenarios of action and their consequences, including ecological, economic and social aspects; the scenarios include cost/benefit analysis;
Development and use of a transparent process, developing and using tools for participation of stakeholders and conflict management and forms of co-operation;
Communication, feedback of the outcome and capacity building;

A project plan for organisation, research and demonstration of sustainable water management in the Pantanal has been developed in co-operation with the groups involved in the region. It has been proposed to develop a river basin approach for the lower Rio Taquari (Pantanal) including the impact of land use activities in the Planalto. This approach includes a study to the hydrological, ecological and land use developments and an integrated approach towards sustainable use. One of the options proposed in the region is the dredging of parts of the Taquari to restore river discharge. In most cases this only is a good investment within the framework of a river or catchment management plan that provides a long term vision and tools for

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the management. On the other side of the spectrum the option has been stated of the establishment of a national park in the flooded area, but also this requires knowledge of the hydrological processes in time and space as well as the consequences for the users.

The Dutch contribution in the water for ecosystems programme is to analyse in co-operation with the institute EMBRAPA-Pantanal the land use processes, the erosion and sedimentation and assess the critical aspects of the river basin. Important issues for biodiversity are identified and together with the regional stakeholders tools for the management of the river basin will be developed. This requires joint hydrological en ecological research, training in socio-economic aspects, in planning and policy co-ordination as well as training in hydraulic/hydrologic modelling.

1.2 The Pantanal and the river Taquari

The Pantanal (85-180m above sea level from west to east) looks like a paradise. There are vast rivers, marvellous wetlands and the land use is extensive cattle breeding, fishing and ecotourism. There are vast rivers, marvellous wetlands and extensive grazing. The Pantanal is the largest complex of wetlands in the world – it is part of the Upper Paraguay River Basin (UPRB). About 80% of the area of the UPRB is located in Brazil. The UPRB comprises an area of 496,000km^2, being 396,800km^2 within the Brazilian borders and the remaining section in Bolivia and Paraguay (99,200km^2). It is made up of large rivers, alluvial fans, lagoons, fossil dunes and salt pans The Brazilian section of UPBR can be divided into 2 main areas: floodplains or Pantanal and high plateaux or Planalto. In Brazil the Pantanal is a declared UNESCO world natural heritage site. All three countries protect discontinuous areas of the Pantanal as national parks and biosphere reserves. In Brazil most of the region is in private possession and unprotected. In Bolivia large areas (about 2 million hectares) are protected (San Matias and Otuquis). Many organisations develop actions for protection, development and management of parts of the Pantanal. Co-ordination in land use, biodiversity conservation and water management is lacking. An important technical issue is the lack of joint data management across borders (Kuhlman and Padovani 2003).

The length of the Taquari is about 800km. Coxim is the border between 'Bacia do médio e baixo Taquari' (Pantanal) and 'Bacia do alto Taquari' (BAT) in the highlands. The size of the high Taquari River basin is 29,000km^2. The total area of the catchment in the Pantanal is about 50,000km^2 and it is the largest alluvial fan in the world. The largest part of the high Taquari is situated in the state of Mato Grosso do Sul, a small part in the state of Mato Grosso. The lower Taquari basin is totally situated in Mato Grosso do Sul. The location in two states makes the river a federal river (under responsibility of the federal government).

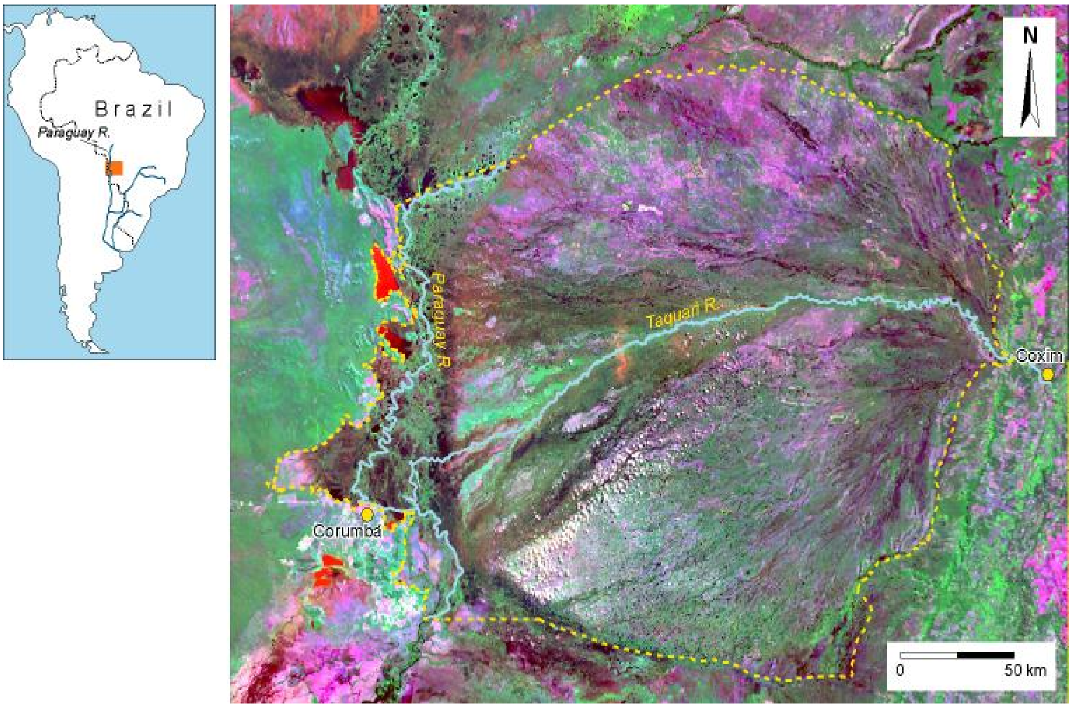


Figure 1.1. The Rio Paraguai and Taquari in the Pantanal, with the major towns Corumbá and Coxím...

The Coxim and Jauru Rivers are the main tributaries of the Taquari and they represent with the upper Taquari one of the major erosive areas of the highlands around the Pantanal, consisting of sandy soils. This erosive character has resulted that the cone of the fan of 11.000km^2 has a permanent flooded area of 5000 to 8000 km^2. This area is situated more or less downstream of Caronal (Figure 1.1).

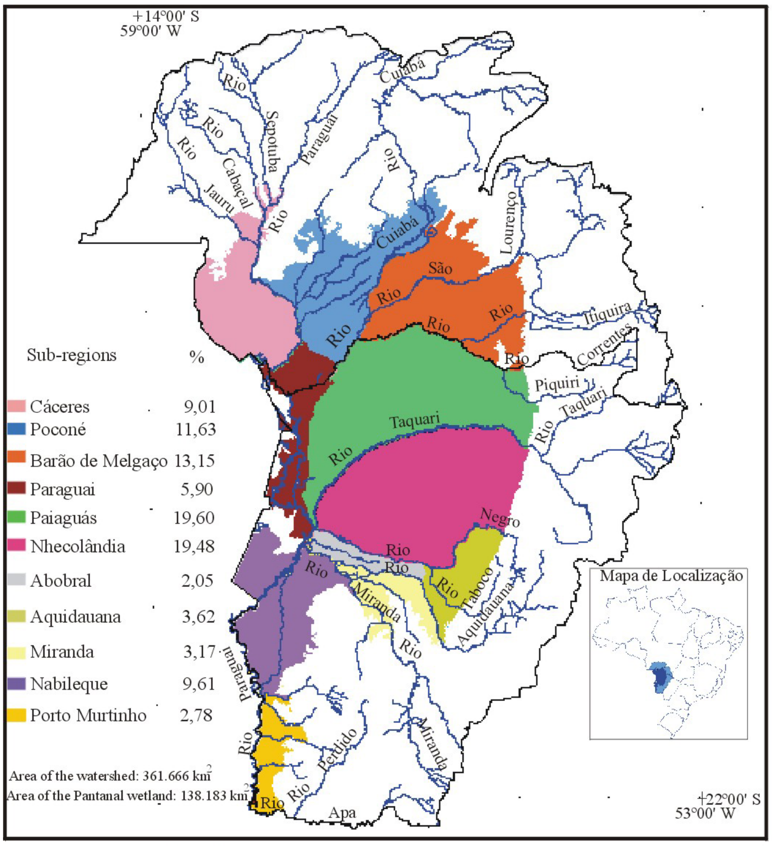
In the upper Taquari the erosive area is about 13,380km^2 (46 %). Here a considerable change has taken place in land use. The loss of soil is high in 12,603 km^2 (44 %) of the total area of 28,451 km^2. The yearly average potential loss here at present is 556 t/ha (Figure 1.2; Figure 1.3). This results in a sediment discharge at Coxim in 1995 of 2000 m^3 per day.

Figure 1.2 Local erosion on the Planalto

Figure 1.3.Erosion gully on the Planalto

The Pantanal in Brazil consists of a number of large rivers in a joint wetland area (Figure 1.4, Figure 1.5). The most important rivers are the Upper Paraguay, the Cuiabá, the Taquari and the Miranda. A zone of 100km wide on each side of the Paraguay is under influence of the river Paraguay (Figure 1.6). Large areas are also dominated by the river regime of the tributaries of the Paraguay and ancient parts such as Nhecolândia characterised by a precipitation dependent system of baías and salinas (Figure 1.7, Dantas et al 1999, Assine and Soares, 2004). In the wet season streams link most of the waters with each other through corixos (permanent linking channels) and azantes (temporary water channels often in old river beds, Figure 1.8). In the wet season large areas of the savannah are flooded (Figure 1.9).

The presently inundated area is situated between the old bed of the Rio Taquari and Corixão in the north. In the lower Taquari two major developments have an impact on biodiversity. The first concerns the sustainability of farming in the region. Farms have to grow in order to maintain economic profitability. Smaller farms below 10,000 ha do not seem to be economically profitable any more (Cadavid Garcia, 1986). This means that farms are increasing in size and trying to find ways for intensification of their production. The cattle density is currently about 0.25 units per hectare. Intensification increases the pressure on biodiversity. The second development is a decline of important plant and animal species such as fish, birds and alligators.



Fonte: Silva e Abdon, 1998

Figure 1.4.The major rivers in the Pantanal

Figure 1.5. Birds eye view on the Pantanal of Paiaguas.

Figure 1.6. The Rio Paraguay with its floodplains

Figure 1.7. Baías (right) and Salinas (left) in Nhecolândia.

Figure 1.8. Vazantes link temporary waters such as baías in the wet season.

Figure 1.9. Flooded grassland savannah (savannah lenhosa)

1.3 Floods in the alluvial fan of the Taquari River

Among the drainage basins that contribute to the seasonal floods of the Pantanal, the Taquari River basin is one of the most important. It has a huge drainage area and is building one of the biggest alluvial fans of the world with an area around 50.000km^2 that means 36% of the Pantanal area (Braun, 1997; Assine & Soares 1998). As other alluvial fans, it is a deposition zone of sediments originated at the highlands.

The increase of the frequency and amplitude of the floods in the Taquari alluvial fan, mainly after 1974, caused permanent floods in some regions, and as a consequence, negative impact in the cattle ranching, fauna and flora. The measures for the flood control in the Pantanal should be mainly of non-structural type, it means that the human population and its economics activities should co-exists with the floods and structural measures should be avoided. Following this way of thinking the mapping for zoning the flood risk areas is very important for the management of the region.

Drainage network

The Taquari alluvial fan is located in the central Pantanal, between the coordinates 17º 00', 54º 30' and 20º 00', 58º 15' (Figure 1.10). A first DEM and the drainage map were extracted from the topographic maps at the scale 1:100.000 of the Brazilian Army. Water level data of the Taquari River at Coxim was obtained from the Agência Nacional de Águas (ANA), the precipitation data was obtained from the Nhumirim Meteorological station located at the Nhecolândia region and the Paraguai River water level from the NAVY station at Ladário city.

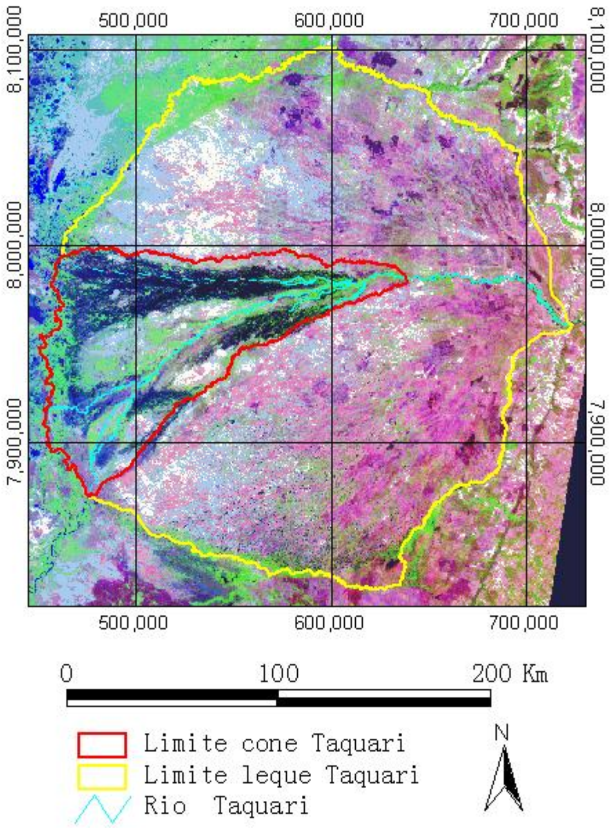


Figure 1.10. Study area showed by a SAC_C satellite image, MMRS sensor, of September 28, 2002, dry season. The alluvial fan boundary is showed in yellow and the active cone boundary is showed in red.

For the mapping of the flooded areas images of the MMRS sensor of the Argentina satellite SAC_C have been used from September 28, 2002 (dry season) and of April 24, 2003 (flood season). The images have been processed for the classification of the flooded areas, extracting the wet index (band 5 – band 2), later this index was joined with the bands 1, 2, 3, 4 and 5 and processed for principal components. The three principal components were processed for no supervised classification of 220 classes, using the ERDAS 3.5 software. The 220 classes were recoded into 2 classes: "flooded" and "non-flooded", using the original image as reference (Padovani et al., 2002).

The drainage of the Taquari alluvial fan presents a typical distributary pattern (Braun, 1997). Over all the alluvial fan, paleochannels can be observed as an evidence of different periods of formation and abandonment of depositional channels as an evolution process that starts at the Pleistocene (Assine & Soares 2004). Most of these paleochannels are active today and joined with the "vazantes", representing the today drainage network, which can be divided in four main flux directions (Figure 1.11).

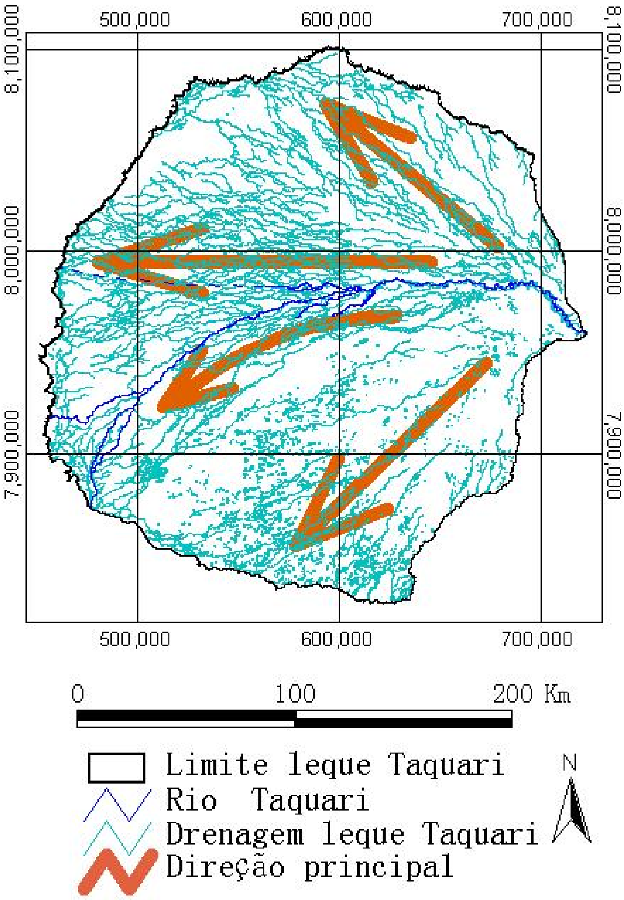


Figure 1.11. Drainage network of the Taquari alluvial fan and the four main flux direction: northwest, west, parallel and to the south of the Taquari River (curved) and southwest.

Just after the Taquari leaves the highlands and enters the Pantanal, it runs over a stretch of around 40km in a straight line in the northeast direction. On this upper portion of the alluvial fan there are few possibilities for avulsions because the river runs inside a meandering belt, with marginal terraces. In this region, on the right side of the Taquari (Paiaguás region), there is a drainage network system with the same preferential flow direction to the northeast, presenting many drainage channels starting close to the Taquari River. This suggests old avulsions and overflows in the direction of the Correntes and Itiquira Rivers. Also on the left side of the river (Nhecolândia region), there is no evidence of avulsions, while the origin of many drainage lines starting close to the Taquari main channel suggest a low risk of avulsions on this stretch.

Downstream, the Taquari River makes a curve to the west, following on this direction around 75 km. The river stays within the meandering belt between the marginal terraces, of which the heights decrease downstream. On this stretch, there are scars of old avulsions on both sides.

After this stretch, the Taquari River channel draws a huge arc to the south. At the left margin, the drainage of the floodplain flows parallel to the Taquari River as a narrow stripe of 15 to 30km wide, making a curve to the south until the meeting with the Paraguay River. At the right margin, many channels starting from broken marginal dikes and levees maintain the flow direction towards the permanent flooded area of the Paraguay River in the west. In this area, the channels of the drainage network are more or less parallel, crossing each other many times, defining an anastomosed pattern (Souza 2002; Assine 2003). This region is a critical area that has suffered heavy environmental and socioeconomic impacts caused by the permanent floods. North of this critical area the drainage network flows to northwest into the direction of the Cuiabá River.

The stretch of the lower Taquari River presents the higher incidence of avulsions with high instability and flood risks in the last decades. The southern part of the alluvial fan is not influenced by the Taquari River, presenting channels and "vazantes", where the flow direction is draining southwest transporting mainly rain water from Nhecolândia towards the floodplains.

Relief

The upper Taquari alluvial fan is among 190 and 200 meters high, located in the eastern boundary of the Pantanal, near the city of Coxim (Figure 1.12).

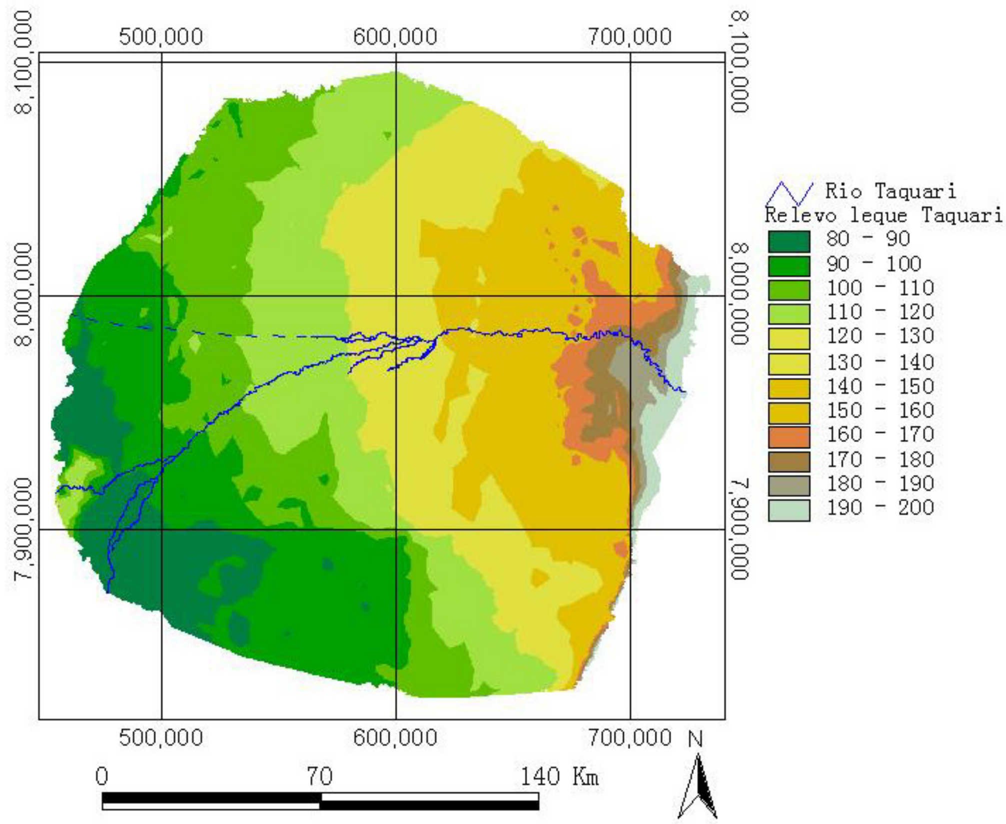


Figure 1.12 Altitude map of the Taquari alluvial fan with height interval of 10meters, from 120m in the east to 80m in the west.

Where the Taquari meets the Paraguai River, in the base of the fan, the heights are around 80 to 90 meters, resulting in a topographic gradient very low along the river of 0,036 m/km (Assine et al. 2004). The contour lines are arcs and the rounded format of the fan looks like a shell with the convex side up. The contour lines are wider to the west, according the topographic gradient decrease and the river comes into the lower portion of the fan.

The flood mapping of recent dry and flood seasons presented a pattern that can be observed in Figure 1.13. In Table 1.1 the areas and percentages flooded and not flooded of the Taquari alluvial fan are quantified.

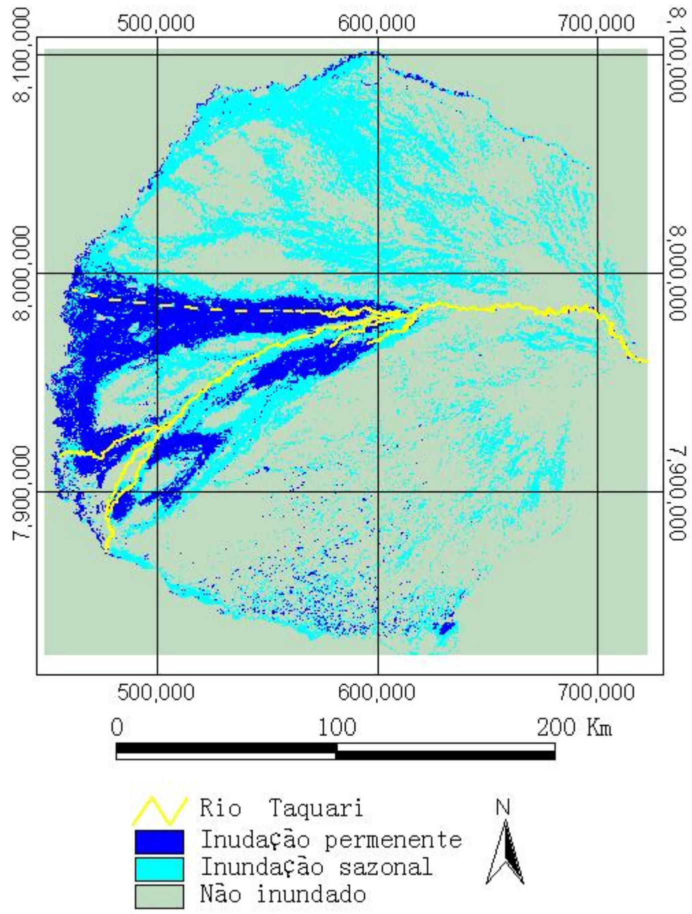


Figure 1.13 Flooded and no flooded areas at September 28, 2002, dry season, in dark blue and at April 24, 2003, flood season in light blue. The Taquari River is in yellow. Images processed according methodology described in Padovani et al., 2002.

Table 1.1. Flooded and no flooded areas in km² and percentages for the Taquari alluvial fan, extracted from the classification of the images MMRS, SAC-C satellite of September, 28, 2002, dry season and April, 24, 2003, flood season.

	Total fan area	Flooded in the dry season	Flooded in the flood season	Not flooded in the dry season	Not flooded in the flood season	Flooded area difference
Value	52.156	6.002	19.534	46.154	32.622	13.532
Percentage	100,0	11,5	37,4	88,5	62,5	-

The flooded area in the dry season, represented 11,5% and in the flood season 37,4% of the Taquari alluvial fan. The 6.002 km2 (11,5%) of flooded area in the dry season represented, to the studied date, the permanent flooded area of the Taquari alluvial fan. The permanent flood, defined as the area flooded in the flood season and that keeps flooded in the dry season, represents 31% of the flooded area in the flood season. The seasonal flood, defined as the difference of the area flooded in the flood season and dry season, represents 69,3% of the total area flooded in the flood season. Table 1.2 shows the quantification of the flooded and no flooded area for the Taquari alluvial cone.

Table 1.2. Flooded and no flooded area (km² and %) of the Taquari alluvial cone, extracted from the classification of images MMRS, SAC-C satellite of September, 28, 2002, dry season and April, 24, 2003, flood season.

	Total area of the cone	Flooded in the dry season	Flooded in the flood season	Not flooded in the dry season	Not flooded in the flood season	Flooded area difference
Value	11.285	5.125	8.218	6.160	3.067	3.093
Percentage	100,0	45,4	72,8	54,6	27,2	-

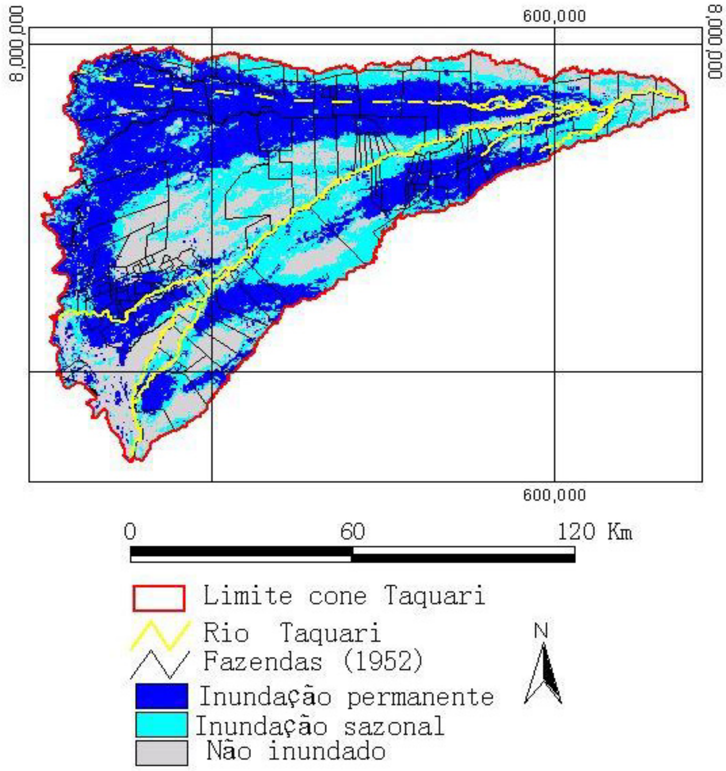


Figure 1.14 Taquari alluvial cone with the farm map of the Eng. Renato Rabelo Vaz (1952), over the flood map. In dark blue the flooded area in April 24, 2003 (flood season), in light blue, the flooded area in September 28, 2002 (dry season). The non-flooded area is in grey. The Taquari is in yellow.

The 5.125 km2, 45,4%) of the area flooded in the dry season represents for the date studied the permanent flooded area of the recent distributary cone of the lower Taquari River. The seasonal flooded area represents 38% of the total area flooded in the flood season while the permanent flood represents 62% of the area flooded in the flood season. The area flooded in the dry season, represents 45% and in the flood season, 73% of total area of the Taquari alluvial cone. The permanent flood, defined as the flooded area in the flood season and that keep flooded in the dry season, represents 62% of the area flooded in the flood season. The seasonal flood, defined as the difference of the area flooded in the flood season and dry season, represents 38% of the total area flooded in the flood season.

The Taquari distributary cone is a critical region because is the most affected area by permanent floods, keeping around half of its area permanently flooded even in the dry season. In the Figure 1.14 the farm map is projected over the flood map of the Taquari recent distributary cone.

For some farms, the permanent flooded area covers almost the total area for the dates analyzed. The anastomosed pattern of the drainage at the right margin of the Taquari, presenting multiple channels sub-parallels and a flow direction to west, explain very well the floods in this critical area of the recent distributary cone of the Taquari River (Figure 1.15).

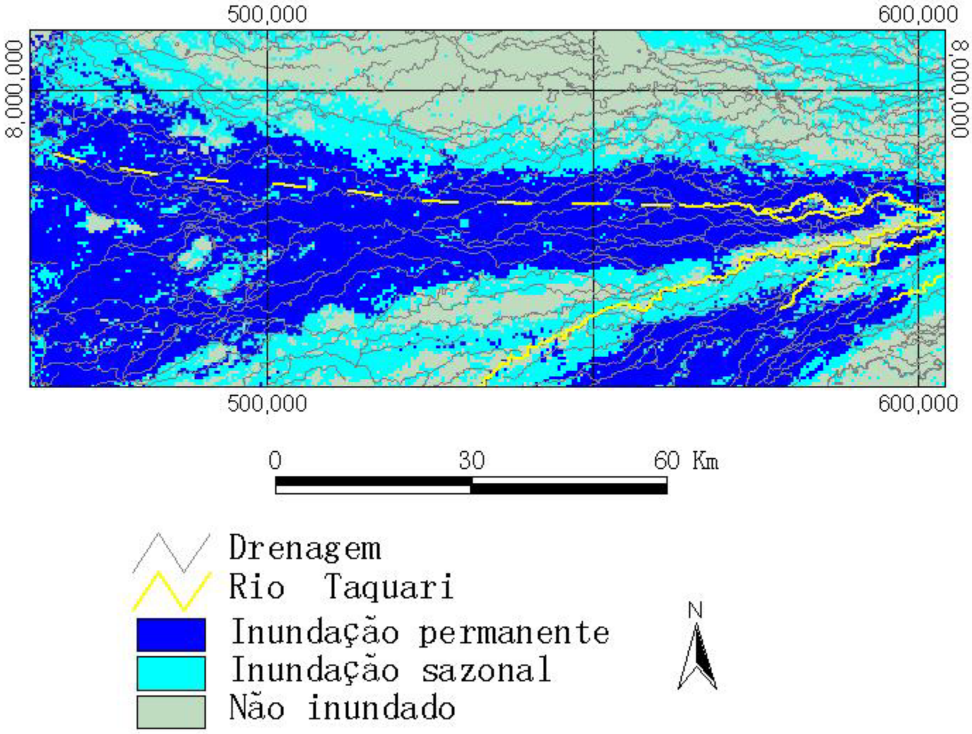


Figure 1.15 Critical area where the drainage is shown in dark grey lines, over the flood map with the permanent flooded area is in dark blue, the seasonal flooded area in light blue and no flooded area in light grey. The Taquari River is in yellow.

Avulsions are frequent in this region and the water overflow is captured by the anastomosed channels, which form a particular drainage network many kilometres away from the Taquari River. These channels conduct the flood water flow to the west onto the Paraguay River floodplain, originating a stripe of permanent flood in the floodplain of the right margin of the Taquari River at the low portion of the alluvial fan.

Floods and sedimentation in the recent distributary cone

Since the 1970s there is an increase of the erosion rate in the high Taquari River basin (Oliveira et al, 1997). Deforestation and inadequate soil management for cattle ranching and some crop plantations are thought to be the causes (Godoy et al., 2002). The sedimentation in the main Taquari channel decreased the water transport capacity causing increasingly flood events in the flood season. In the upper part of the fan, floods from the Taquari only influence a restricted area because the river meanders in an incised bed bordered by terraces.

Downstream, in the recent distributary cone the marginal terraces disappear and the Taquari change into a distributary pattern. In this area there is a significant loss of water to the side floodplains (Ministerio de Interior de Brasil, 1974, Ministerio de Interior de Brasil, 1979). Galdino et al., (1997), showed that the water loss of the Taquari River to the floodplain is the cause of the foods in the recent distributary cone.

The water loss to the floodplain and consequently the floods, do not occur only by overflows at high water levels as in many other floodplain rivers as the Paraguay, Miranda or Cuiabá Rivers, but mainly by broking marginal dikes and levees (locally called "arrombados").

The water of the Taquari looses energy when it spreads over the floodplain and the suspended sediments are deposited. This processes of dissipation of the water flow loaded with sediments, forming avulsion complexes can be observed with satellite imagery (Assine, 2003). At present, this process can be clearly observed in the Caronal farm located at 18°17'08"S, 55°58'00"W (Figure 1.16).

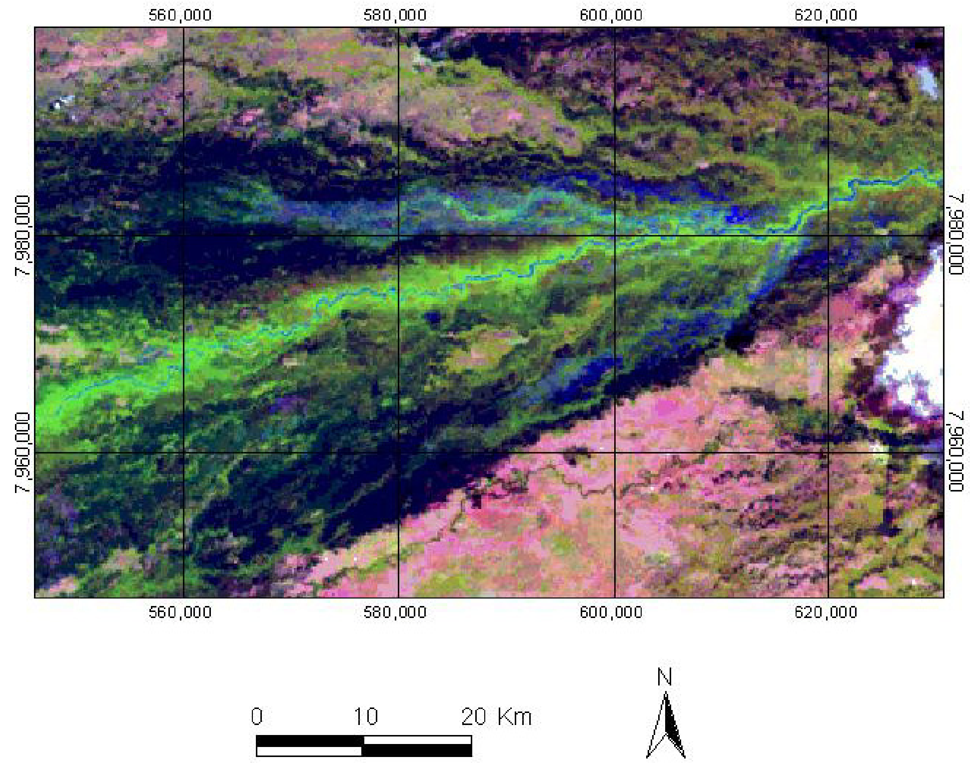


Figure 1.16 "Arrombado" stretch of Caronal farm (18°17'08"S, 55°58'00"W). Image of MMRS sensor of the Argentina satellite SAC-C, of March 04, 2002, flood season. The suspended sediment clouds are in blue colour at the left and right sides of the Taquari.

The avulsion complexes occur when the water that flows from the broken dikes do not return to a new channel in the floodplain. Sediments of different sizes are deposited in a complex way. The fine sand, is heavier and represents more then 80% of the suspended sediments of the Taquari River (Padovani et al., 1998b), depositing closer the Taquari River. The clay, lighter, keep itself suspended in the water, being carried out and deposited downstream the avulsion lobes. This behaviour can be observed from the satellite images. The origin of the flooding can be identified as the water loaded with sediment has a blue colour using the band 5 (mid-infrared), band 4 (reflective-infrared) and band 3 (red) Landsat band composition (Figure 116).

The sedimentation in the floodplain is fast because of the heavy sediment load of the Taquari River waters (Padovani et al., 1998a; 1998b). A distributary channel can be formed fast, developing marginal dikes and the avulsion process is completed with the migration of the main river channel. The migration of the River at the "arrombado" Zé da Costa, occurred in the lower stretch of the River in the 1990´s (Padovani et al., 2001). A similar, but stronger process is occurring at present in the upper distributary cone in the stretch at the Caronal farm and can cause a tremendous change in the Taquari River channel (Assine, submitted).

The role of the rain and the Paraguay River

The water level peaks of the Taquari River and the rain data peaks, match each other (Figure 1.17), showing that the Taquari water level is directly related to the rain in its drainage basin as a fast response way. However, between the Paraguay River peak flow and the peaks of rain and of the Taquari River, a time lag of some months can be observed. The floods of the Paraguay River influence the floods of the lower Taquari cone, making it longer and increasing the amount of floods. The Taquari flood wave that starts in December at the lower Taquari, extends until April due to the rising water of the Paraguay River that holds the Taquari waters, working like a dam. This interaction between the Taquari and Paraguay Rivers and the rain, was already described (Hamilton, et al., 1995, Galdino et al., 1997) and will be analysed further here.

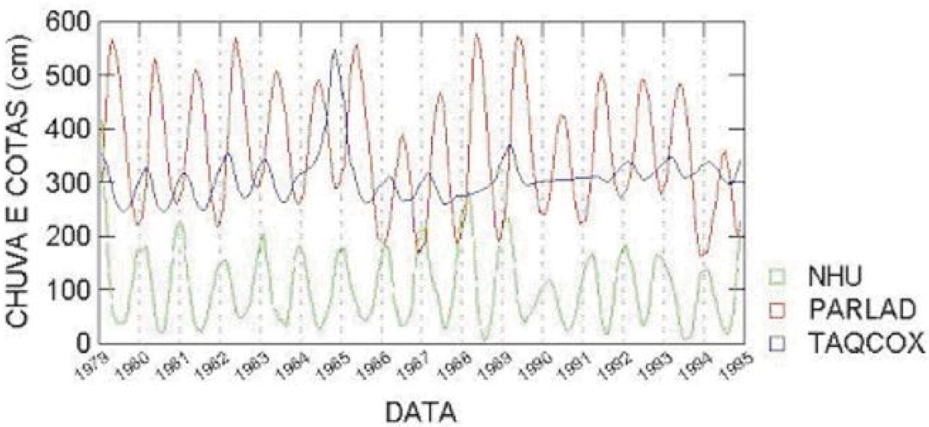


Figure 1.17. Distribution of Taquari water level at Coxim (TAQCOX, below), Paraguai River at Ladário (PARLAD, centre) and rain data at Nhumirim farm (NHU, upper). The data was smoothed using the median.

The hydrograph of the Paraguay River at Ladário, shows that the water levels increased from 1974 to present, after the dry period of 1963 to 1973 and that the water levels before 1963 were lower than at present, suggesting the influence of climatic changes in the floods of the lower Taquari cone (Galdino, 1997; Ministerio de Meio Ambiente, 1997, Soriano et al., 2001).

Interventions in the main Taquari channel

Rich farmers, poor farmers and professional fishermen make interventions of opening and closing "arrombados" in the Taquari River. In the dry period of 1963 to 1973 "arrombados" were opened artificially to conduct water to the cattle as occurred in the Taiamã farm, where the old building to take water from the Taquari to the field still exists. This particular building was planned and executed by the PRODEPAN (Programa Especial para o desenvolvimento do Pantanal). In the last decades due the increase of the floods the most common intervention has been the closing "arrombados" by the farmers to protect their land against floods. In this process dredges, plastic bags with sand, tree branches and trunks are used to make an artificial dike to close the "arrombados" (Figure 1.18). There are rumors that professional fishermen open these artificial "arrombados" closed by the farmers to facilitate fishing. The interests of fishermen and farmers do not coincide in this point.

Apart from the "arrombados", the farmers have done interventions when the River margin erosion threatens houses or other building of the farm. An example is the farm located at the coordinates 56º 23´34.24" O e 18º 21´52.86" (Figure 1.19), where the farmer made a channel to deviate the Taquari River that was eroding the shore and was threatening the main house.

Figure 1.18 "Arrombado" called "boca or barco de ferro" that was closed by farmers and opened by professional fishermen, according local people.

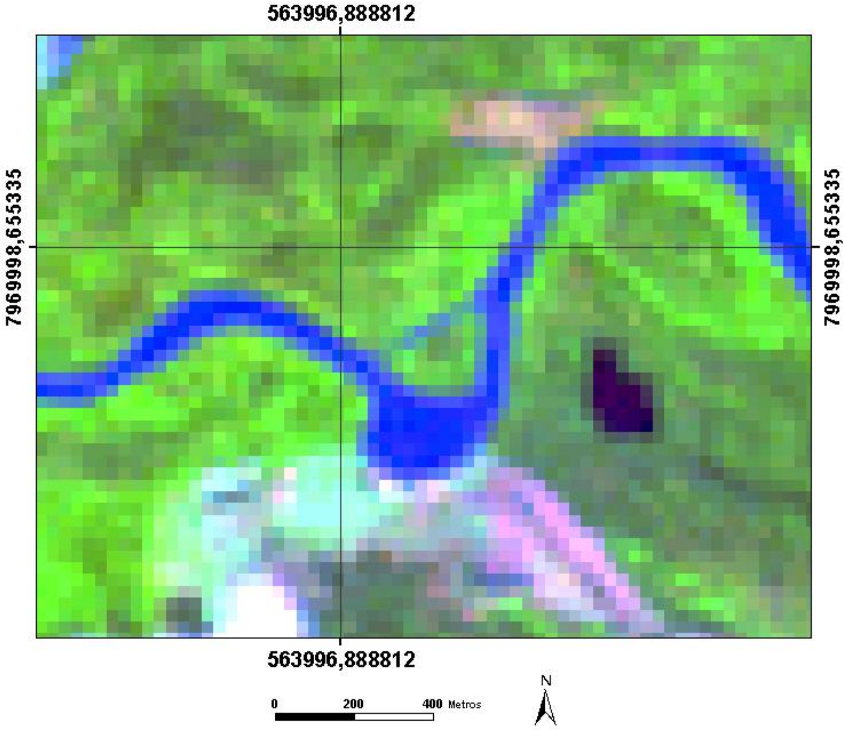


Figure1.19 Channel to deviate the Taquari River at a meander with strong margin erosion.

1.4 The environmental problems of the Taquari

Erosion and silting up make the major rivers of the Pantanal and especially the river Taquari into an unstable system leading to economic and ecological problems due to increasing flooding with serious threats for the fauna, flora and economy of the Pantanal. According to the people in the Pantanal the main causes are in the agricultural use of the cerrado, the dry savannah forest of the Planalto, since the early 1970s. The sanding up of the Rio Taquari is at the moment a major problem, because of the nearly permanent inundation of an area of about 11,000km^2 in the sub-region Paiaguás. To solve that problem is difficult as there is no coherent river management system and the behaviour of the river, especially in the lower reach is unknown. The knowledge to make decisions for tackling both problems is lacking and should be acquired through this joint project.

The relief and drainage flow direction and structure explain most of the floods in the Taquari alluvial fan and cone and should be considered in projects of conservation, intervention or restoration of this area. The flood quantification, mapping and monitoring of the Taquari alluvial fan together with the hydrological data analysis are important tools for the management of this area for economic or conservation activities.

The Taquari alluvial cone presents particular characteristics that distinguish this area from the Paiaguás and Nhecolândia region, and in this way can be considered as an independent subregion of the Pantanal, the subregion of the Taquari alluvial cone.

Interventions made by local people can influence the floods of the Taquari alluvial fan and need to be taken in account in further studies or projects. In the present stage of the study the causes of the changes in the river system can be considered both natural and man induced:

- Natural river processes
- Climate change → increased precipitation:
  - Increased erosion and sediment transport
  - Changes in vegetation: increase in superficial and subsurface flows
- Land use changes and related vegetation changes (Figure 1.20)
  - Increased erosion and sediment transport
  - Changes in discharge patterns due to drainage
  - Changes in vegetation: increase in superficial and subsurface flows
- Incorrect river management

The main problem that has been indicated by the people living in the area of the Pantanal has been the national colonisation in the 1970s that completely changed the land cover and land use on the Planalto.

Economic consequences of Biodiversity decline can be:

- Less direct income through fisheries and hunting
- This means for the Pantanal:
- Less ecotourism and fishing tourism in the Pantanal
- Less air transport and more isolation due to decline in tourism
- Smallholders will increasingly become dependent on public support
- Capital leaving the region

The Role of Science is to develop the basic knowledge on:

- The river system, its hydrology and sediment transport;
- The land use system, economic and environmental development;
- The biological system, the functioning of the river basin as an ecosystem;
- The social and political system and its functioning;

This knowledge will later be integrated into a database and a in a later stage a Decision Support System. This will be done through knowledge development for the Taquari by:

- Integration of existing data
- Hydraulic model for the Taquari (water and sediment discharge);
- Model for land use and habitats;
- Identification of indicator species for impact analysis with LEDESS;
- Modelling different scenarios of change in cooperation with stakeholders: more sediment, less sediment, more water less water, regulation.

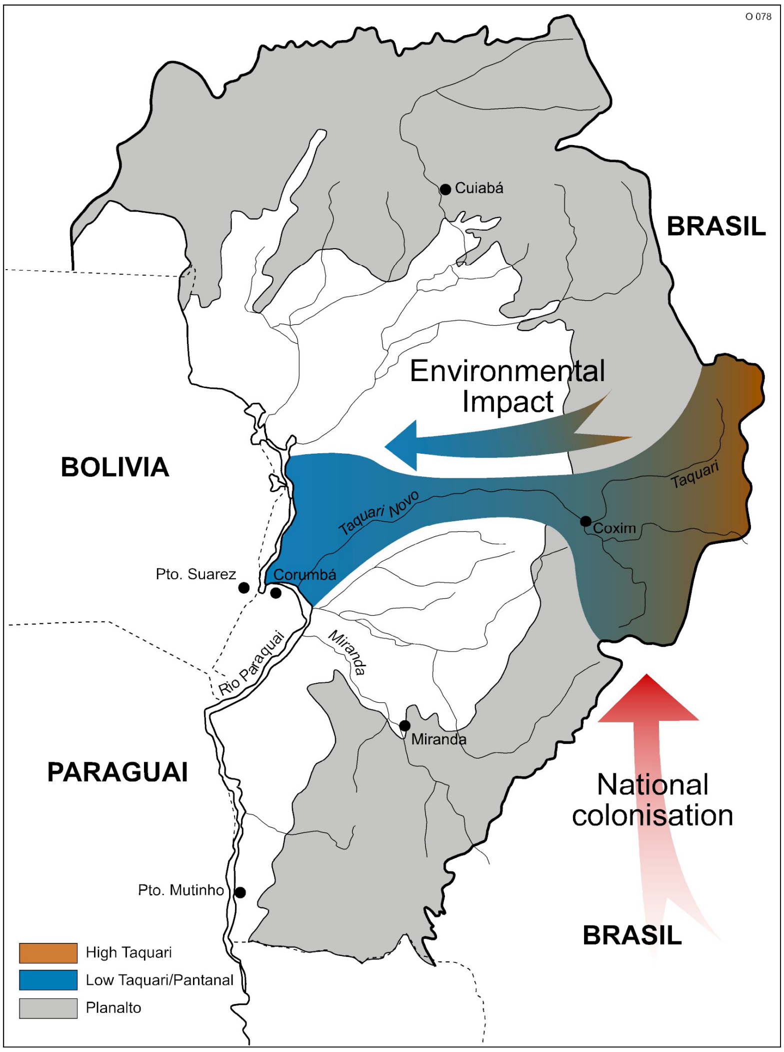


Figure 1.20. Supposed relationship between demographic and environmental impacts in the Taquari Basin.

1.5 The approach

Along its course, every river changes its ecological structure and function. The concept dominating ecological river studies for the last decades was the River Continuum Concept (Vannote et al 1980). Energy in the form of biomass and detritus is constantly flowing downstream, hence the energy of any particular section of the river are influenced by events upstream. The result is a longitudinal continuum of ecosystem structures with a number of predictable properties.

Running waters are, however, far more than mere longitudinal river corridors and modern ecology recognises them as complex systems. According to Townsend and Riley (1999) the science of river ecology has reached a stage where explanations for patterns rely on links at a variety of spatial and temporal scales, both within the river and between the river and its landscape. The links operate in three spatial dimensions:

Longitudinal links along the length of the river system, such as the River Continuum (Vannote et al 1980), downstream barriers to migration
Lateral links with the adjacent terrestrial system, such as the Flood Pulse Concept (Junk et al 1989).
Vertical links with and through the riverbed (Hyporheic Corridor Concept, Stanford & Ward 1993)

The lateral and vertical dimension of the ecosystems is associated with running water. The Flood Pulse Concept (Junk et al 1989) states that the pulsing of the river discharge that extends the river into the floodplain is the major force controlling biota in rivers with floodplains. The flood pulses control biota in three ways: directly by (1) facilitating migration of animals, indirectly by (2) enhancing primary production in the floodplain and by (3) habitat structuring. The floodplains provide important factors for driving ecological processes in the riverine ecosystem. During floods biota migrate both actively and passively between different habitats in the river floodplain system, where they feed (Wantzen et al 2001). The lateral exchanges between main channel and floodplain, and nutrient recycling within the floodplain has according to Grift (2001) more direct impact on biota than by the processes described in the River Continuum Concept. Fish, mammals and plants move along their corridor in different speed and with different steps. The strong interaction between the river and the riparian ecosystems in its ecotone provide a huge exchange of energy, matter and nutrients. Networks of river corridors maintain the genetic exchange between populations in natural and impacted landscapes.

The dynamic flow of river water also has an important function by shaping the physical structure of the riverine landscape (Ward et al 2002). The permanent natural changes of habitat structure and connectivity are a warrant for a high biodiversity (Tockner et al 1999) and for an efficient use of floodplain-borne resources by different kind of biota and mankind (Junk 2000, Junk and Wantzen 2004).

The Pantanal-Taquari project aims at to analyse how river management, farming and other socio-economic activities like tourism with biodiversity conservation in the Pantanal are linked with biodiversity and ecological processes. It is based on existing knowledge, but it also identified gaps in knowledge and filled these gaps through interaction with stakeholders, research to improve planning, policy and management. Existing and ongoing EMBRAPA projects on the alluvial part of the Taquari have been integrated.

1.6 The structure of the Report

The Report is consists of eight chapters. In the first chapter a short description has been given of the Pantanal and the Taquari and the problems that occur there at present. The approach is presented as well as the initial problem statement and potential causes.

In chapter 2 the geomorphology, avulsions and sedimentation processes are placed in the historical context helping to understand the natural processes behind the sedimentation in this large alluvial fan. For analysing other causes and consequences a Digital Elevation Model and an Hydrological Model are needed for understanding the present flooding processes. These are treated in chapter 3 and 4. In chapter 5 the present river flooding and sedimentation is being analysed.

In chapter 6 the consequences of the flooding patterns and processes are analysed for biodiversity and land use. In chapter 7 these are placed in the socio-economic context and the context of decision making and river basin organisation.

Finally in chapter 8 possible solutions for flooding are treated based on the ideas presented in the different stakeholder workshops and on the ideas that came out of the interviews. The consequences in economic, ecological and land use aspects are shortly presented. The chapter ends with a short discussion on the potential follow-up and the lessons learnt from this project.

2 Avulsions, flooding and sedimentation in a geomorphological perspective

Bart Makaske[4]

2.1 Introduction

The geomorphological study of the lower Taquari River aimed at determining the causes of the increase in flooding and sedimentation. The foundation for modelling of ecological changes and evaluation of management options is a proper understanding of the geomorphological evolution of the lower Taquari River and its floodplain. In other words: sometimes the past is the key to the present. Therefore, in this study ample attention is paid to reconstruction of the geomorphological history of the study area in order to establish fundamental processes and trends that continue today. A large-scale approach is adopted, with a focus on channel-floodplain interactions. The present study area comprises the floodplain influenced by the Taquari, which includes the Taquari alluvial fan and the neighbouring part of the Paraguai river floodplain, where Taquari and Paraguay floodwaters meet (Figure 2.1).

This chapter is based on data and ideas discussed in a workshop with Brazilian and Dutch experts (Corumbá, August 2003), data collected during a river survey (March-April 2004), a survey of the literature and an analysis of remote sensing data.

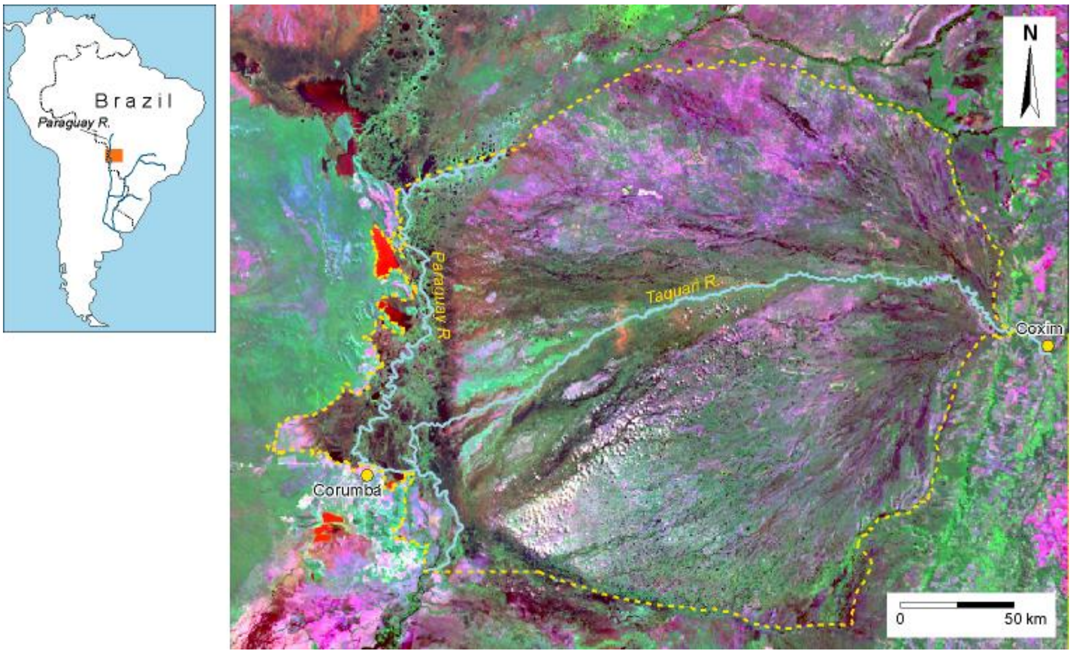


Figure 2.1 Satellite image (LANDSAT TM) of the study area, showing the Taquari alluvial fan and the neighbouring Paraguay River floodplain in south-western Brazil.

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2.2 General characteristics of the study area

The Taquari River is a tributary of the Paraguay River (Figure 2.1). Where the Taquari enters the Pantanal lowlands, its mean annual discharge is around 400m^3/s [period since 1973 (Galdino et al., 1997, Padovani et al., 1998a)]. The Taquari discharge is highly seasonal with mean peak discharge around 1100m^3/s (Collischon et al., 2001), whereas a maximum discharge of 2369 m^3/s has also been recorded (Padovani et al., 1998a). During the dry season, discharge decreases to a minimum of about 200 to 250m^3/s (Padovani et al., 1998a).

The Taquari drains the São Jerônimo Plateau and flows westward into the Pantanal basin. Twenty kilometres downstream of the town of Coxim the river enters the lowlands, where it has built a giant alluvial fan. The river is incised in the upper fan over a length of approximately 100km. In this reach the river is strongly meandering and due to entrenchment its present floodplain is up to 5 m below the fan surface (Assine & Soares, 2004). Downstream, on the lower fan, the river is no longer entrenched and spreads out on the fan surface in a distributary/anastomosing pattern, with straight (laterally stable) channels (terminology cf. Makaske, 2001). This reach is about 150km long. In its lowermost reach, the Taquari River flows for 25 km across a low-gradient floodplain that is principally built by the Paraguay River.

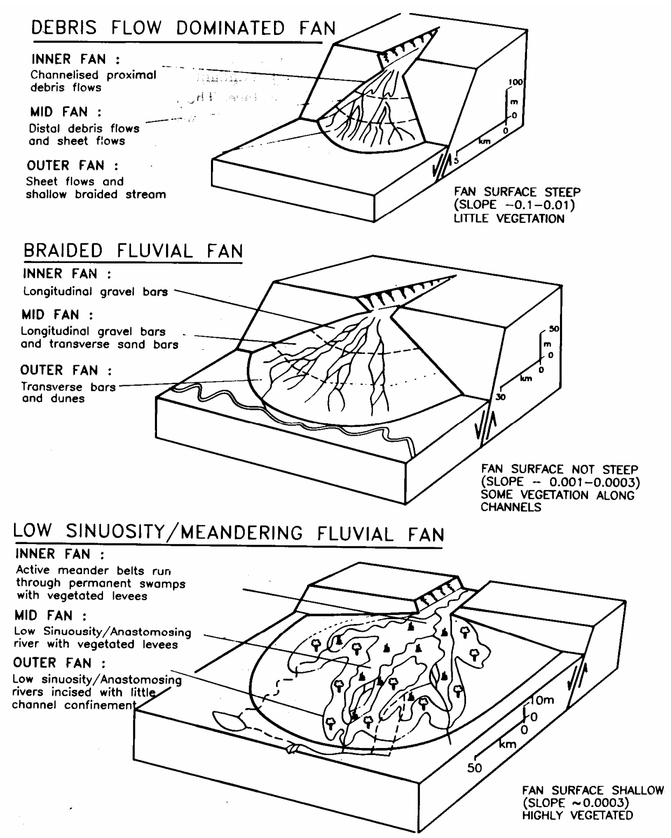

Figure 2.2 Three types of alluvial fans, with different morphology and processes (from Stanistreet & McCarthy, 1993).

In a number of aspects, the Taquari alluvial fan differs from many other alluvial fans reported in the scientific literature. Most fans described hitherto are relatively small-scale phenomena, measuring up to few kilometres across. Such fans tend to occur in semi-arid climatic zones, are scarcely vegetated and are formed by braided rivers with flashy discharge. These fans are steep and debris flows significantly contribute to fan building (e.g. Blair & McPherson, 1994). In contrast, the Taquari fan with its radius of 250km is very large and its average gradient of 24 cm/km can be classified as low. The fan is well vegetated and, although discharge is seasonally variable, the Taquari experiences year-round flow, being fed by groundwater from extensive sandstone aquifers (Baker, 1986). In fact, the Taquari fan represents a good example of a 'low sinuosity/meandering fluvial (Figure 2.2). Few examples of this type of fan have been described worldwide. The Okavango Delta in Botswana represents a particularly well-studied low sinuosity/meandering fan (e.g. Stanistreet & McCarthy, 1993).

Climate in the study area is humid, with spatially variable yearly precipitation in the area roughly ranging from 1100 to 1800mm (Galdino et al., 1997). Rainfall is markedly seasonal: December and January are the wettest months with average monthly precipitation well over 200mm in most of the area, whereas July and August are dry with average monthly precipitation mostly below 30mm. Temperatures are much less variable over the year. Average daily maximum temperatures are between 30 and 35° C all year round. Only during the winter (June-August), average daily minimum temperatures drop slightly below 20°. In the Köppen classification the Pantanal climate can be described as "Aw", which stands for a humid tropical climate with summer rain and a relatively dry winter period.

2.3 General geomorphological processes on alluvial fans

Three basic processes typify alluvial fans in general and therefore also play a role in the present study area.

1. Rapid aggradation in active lobes
Generally, alluvial fans are rapidly aggrading sedimentary environments. However, within alluvial fans, aggradation is strongly localized and occurs almost exclusively in a more or less triangular area, termed the active lobe. The active lobe usually covers parts of the lower to middle fan zones.

2. Channel entrenchment on upper fan
Often the channel that feeds the active lobe with sediments and water is incised in the upper parts of the fan (Figure 2.3). This incision can have multiple causes: (a) reduced sediment supply from the catchment, (b) reduced subsidence of the sedimentary basin relative to the source area, (c) climatic changes resulting in a more erosive river regime, (d) autocyclicity of the fan system. Obviously, reduced sediment supply may be caused by climatic change but may also be caused human interventions, such as damming of rivers or reforestation. Schumm (1977) described a form of autocyclic behaviour of fans leading to periodic upper fan entrenchment.

Autocyclicity of the fan system may also relate to the recurrent process of fan-lobe switching, addressed in the next paragraph. In practice, river entrenchment on the upper fan is mostly a complex response to multiple causes.

3. Avulsions and fan-lobe switching
River avulsion, i.e. a 'sudden' switch from an existing river course to a completely new river course, occurs relatively frequently on alluvial fans. This is due to the convex-up shape of the floodplain, offering multiple energetically favourable flow paths to the river. The process of avulsion involves the diversion of flow from an existing river channel onto the floodplain where a new channel is formed, that eventually may take over all discharge from the old channel (Makaske, 2001). In the initial stages of avulsion, massive amounts of sediment-laden waters are routed from the river channel to the floodplain. Later, complex channel patterns may form (Figure 2.4), from which a new main channel develops (Smith et al., 1989). Two types of avulsion on alluvial fans can be distinguished: (1) avulsions within the active fan lobe, (2) avulsions causing the formation of a new fan lobe (fan-lobe switching). For fan-lobe switching to occur, sedimentation within the entrenched part of the alluvial fan is needed. One of the mechanisms is backfilling of the entrenchment, associated with aggradation of the active fan lobe. Once a major avulsion has occurred, incision will start again. The alternation of sedimentation and erosion in response to fan-lobe switching is a form of autocyclic behaviour of alluvial fans.

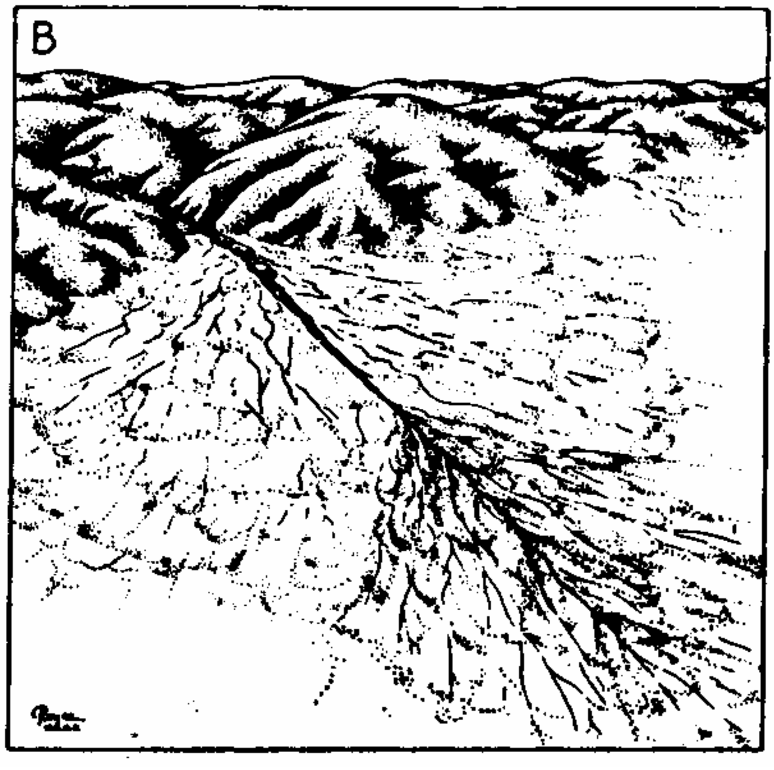

Figure 2.3 hannel entrenchment on the upper fan and downstream shift of alluvial fan sedimentation. [From Bull (1968) in Schumm (1977)]

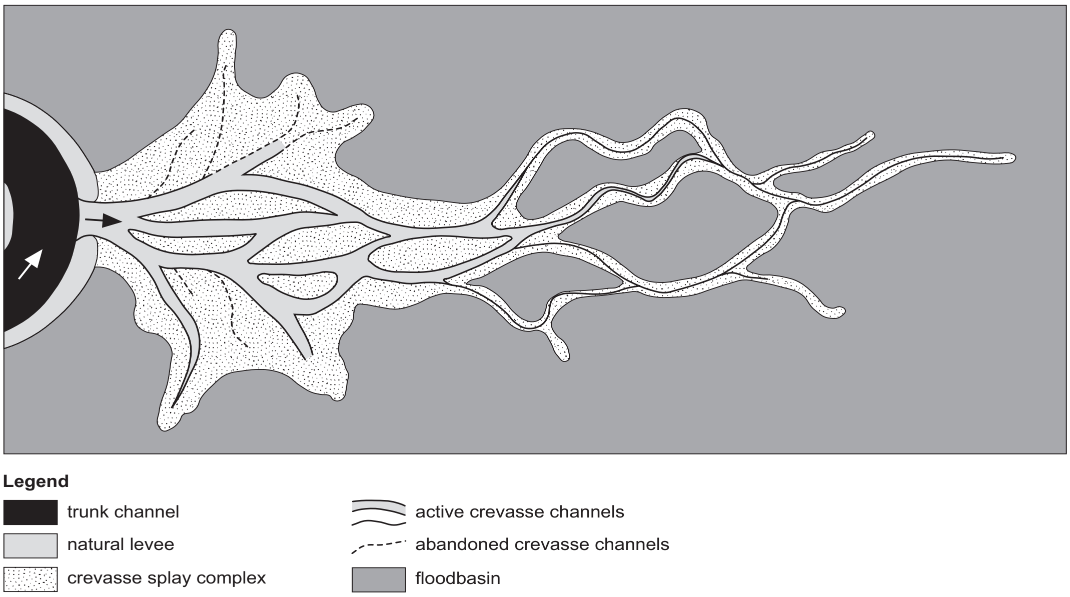

Figure 2.4 Anastomosing channel pattern within a developing avulsion belt. From the initial massive crevasse splay complex shown on the left, narrow lobes with channels prograded to the right, eventually rejoining and enclosing parts of the floodplain. (from Makaske, 2001)

2.4 Eomorphological evolution of the study area

Numerous abandoned channels can be observed on the alluvial fan as well as on the neighbouring Paraguay River floodplain. A relative chronology of the fluvial landforms in the study area is established by a study of satellite images (LANDSAT TM, JERS radar image). Also a geomorphological map of the study area was produced from these sources that were used in the LEDESS model (chapter 6). As to the older forms in the study area, relative ages were estimated for different fan lobes. Within the present active lobe and the Paraguay River floodplain, different channel belts could be relatively dated. The relative chronology presented is a hypothetical product, waiting further testing by geochronometric dating (^{14}C and OSL).

Abandoned fan lobes

The oldest forms in the study area, except for the bedrock outcrops in the Paraguay River floodplain, are located in the Nhecolândia area (Figure 2.5). This area is obviously part of the Taquari alluvial fan and is covered by numerous small ponds, measuring a few hundred metres to a few km across. These (semi)circular ponds are often surrounded by ridges of fine sands that can be interpreted as lunette sand dunes (Assine & Soares, 2004). Many ponds seasonally dry out and can be considered salt pans. Relic drainage patterns, associated with fan-lobe formation, are strongly degraded and are older than the formation of the ponds. Active drainage systems seem groundwater-fed and rise in the middle-fan zone. Aeolian forms and strong degradation of original fan-lobe drainage suggest that this fan lobe was exposed to Late-Pleistocene arid climatic conditions, with low groundwater tables.

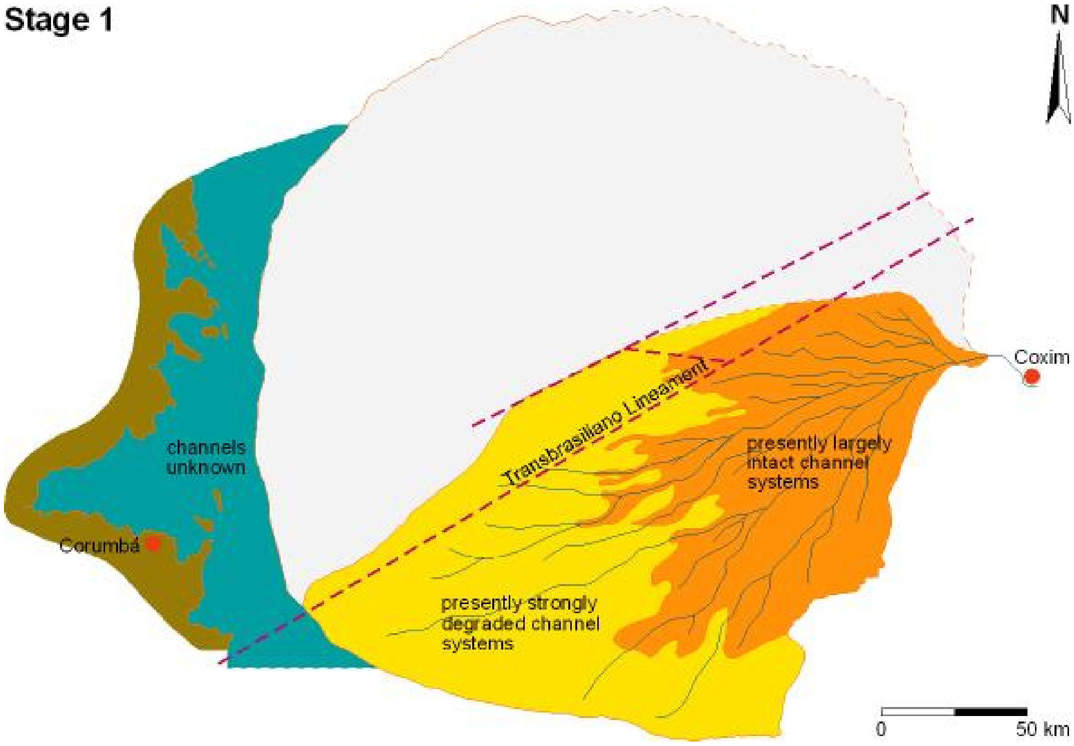

Figure 2.5 Formation of the southern part of the alluvial fan: the oldest fan lobes presently exposed.

The strongly degraded fluvial forms of the Nhecolândia area on the lower portion of the southern Taquari fan, grade upstream into a more intact fan-lobe complex on the upper fan (Figure 2.5). Drainage patterns in this area show fresher morphology, whereas the (semi)circular ponds that typify the lower southern Taquari fan, are much fewer in number and only occur between the channel belts. It is unclear whether formation of this complex was contemporaneous with degradation of the lower fan. One can image that under the Late-Pleistocene arid conditions only the upper portion of the fan remained active with distributary systems ending up in a playa environment on the lower fan. Alternatively, it may have been that under arid conditions degradation of fluvial channel systems also took place on the upper fan and that a return to more humid conditions around the Pleistocene-Holocene transition caused reactivation of the upper fan systems. A number of the present groundwater-fed channel systems on the lower fan seem to rise between sub-lobes of the upper complex. The considerable age of the upper complex is also suggested by subsurface ferruginous duricrusts observed a few meters below the surface in a cut-bank of the Taquari. Generally, formation of such duricrusts takes at least several thousand years.

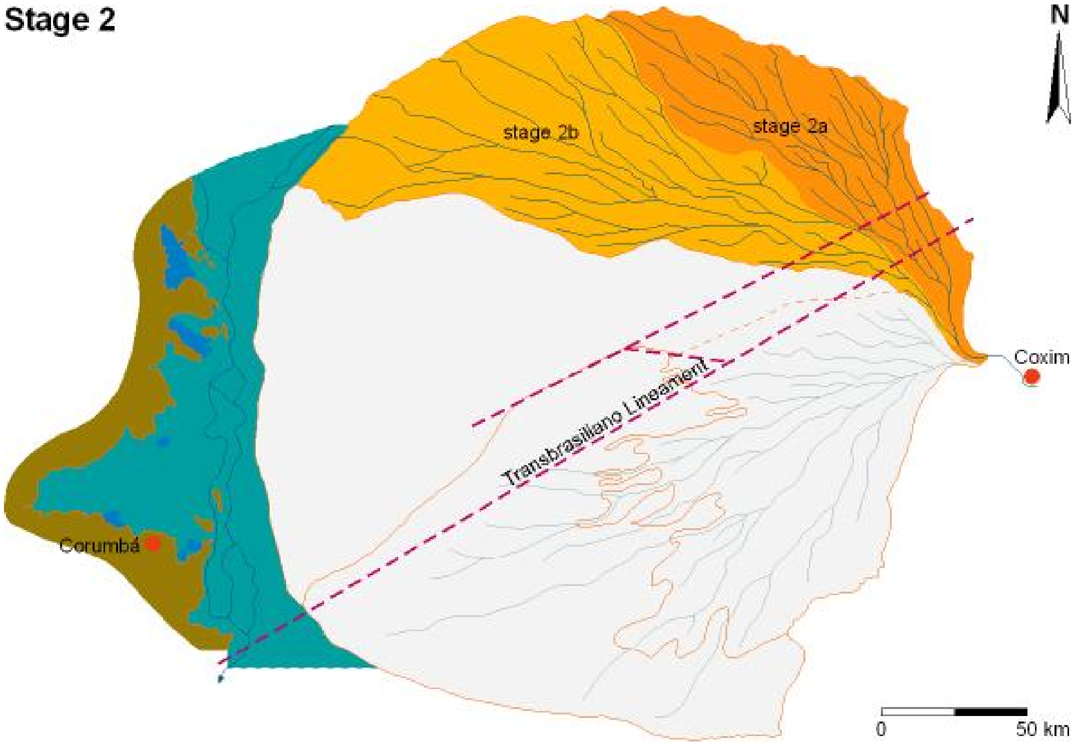

Figure 2.6 Successive formation of the two oldest northern fan lobes, presumably during early to middle-Holocene times.

Likely as a response to increasingly wetter conditions during the early Holocene, a new fan lobe developed north of the present Taquari, along the mountain front (Stage 2a in Figure 2.6). The inability of the degraded channel systems on the southern fan to cope with increasing discharges might have been a prime cause of the major avulsion that took place at the apex of the fan (i.e. the location where the Taquari crosses the mountain front). Tectonic movements along the Transbrasiliano Lineament must have created a favourable gradient and in this way contributed to this northward shift in fluvial activity. Deposits probably belonging to this fan lobe were studied in a cut-bank of the Taquari. The 4-m-thick succession studied consists of an alternation of fine sand (D50<250 μm) and clay beds, some of which represent channel-fills. Incipient ferricrete formation with big (diameter 1-2 dm) iron oxide nodules, was observed at 1.4 to 2.0 below the surface.

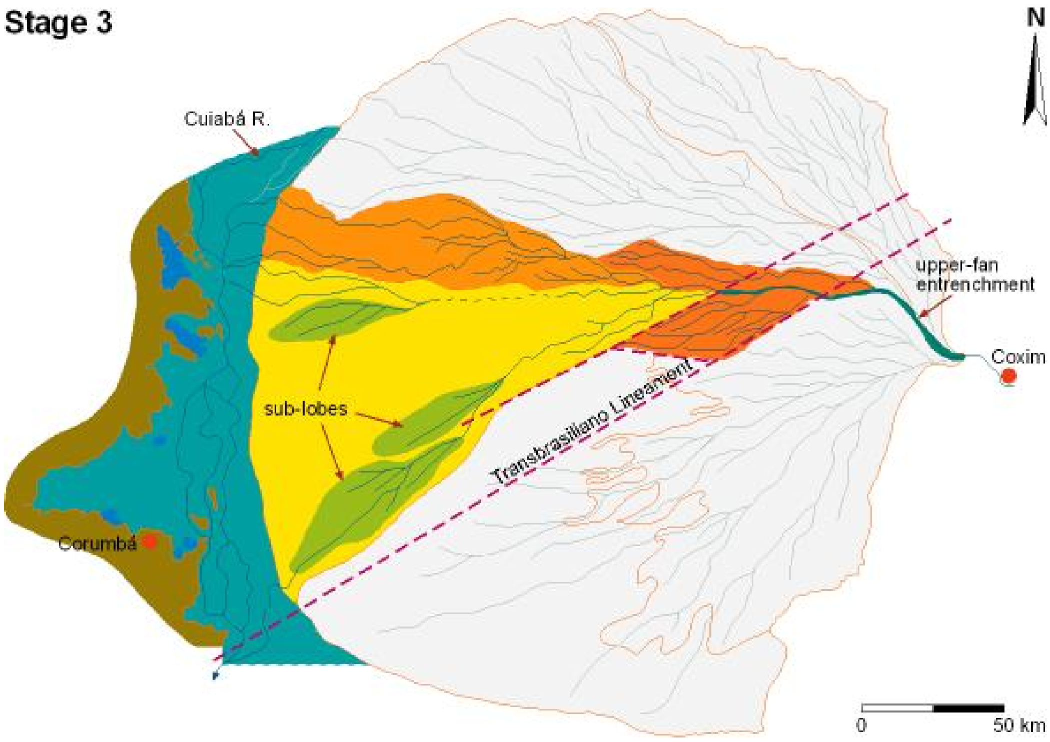

Figure 2.7 Establishment of westerly drainage on the Taquari fan, presumably during the late Holocene. After formation and incision of a relatively small lobe on the central upper fan, a new fan lobe reaching to the edge of the fan developed. Probably more or less at the same time, the present active fan lobe was initiated.

Rapid aggradation of the first northern fan lobe resulted in the development of progressively steeper gradients in a west-north-western direction, which ultimately resulted in a major avulsion on the upper fan near the location where the present Taquari River turns west. A relatively large fan lobe developed in the central part of the northern fan (Stage 2b in Figure 2.6). On its north-eastern edge, drainage patterns of this new lobe cut the drainage of the previous lobe. This lobe is believed to be roughly middle Holocene in age.

A following major avulsion approximately at the same location as the preceding one caused the present westerly direction of the Taquari drainage on the upper fan. A relatively small fan lobe developed on the upper fan. It seems that this lobe remained small because it was soon incised by the Taquari. Causes for this incision are unknown. The intersection point (the point on an alluvial fan where upstream incision switches to downstream aggradation) shifted downward to near its present location. A new distributary system reaching downstream to the edge of the fan developed downstream of the intersection point. The associated fan lobe is located just north of the present active lobe. Incision and downstream shifting of fluvial activity on the alluvial fan occurred presumably during late-Holocene times. Probably more or less contemporaneously, formation of the present active lobe started (Figure 2.7).

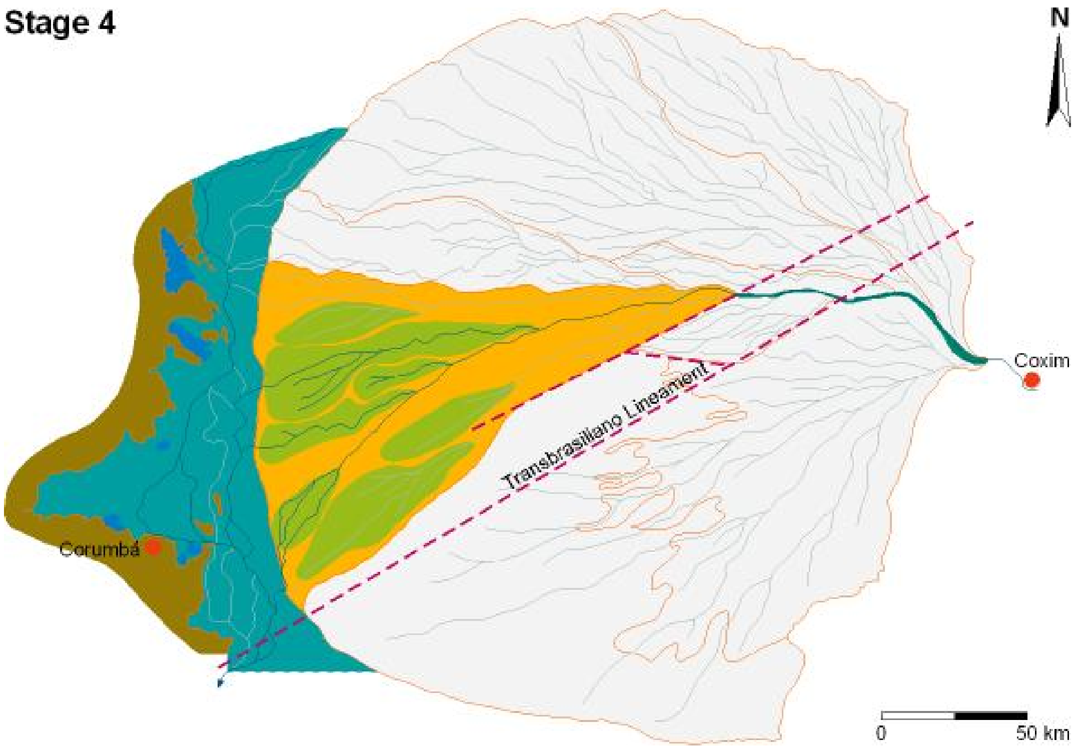

Figure 2.8 An important avulsion on the middle fan led to the establishment of the present Taquari River. Three sub-lobes representing former avulsion belts were successively deposited on the lower fan.

Active fan lobe and Paraguay River floodplain

Within the present active lobe, a number of channel belts and associated sub-lobes are discerned. The sub-lobes can be considered (abandoned) avulsion belts (cf. Smith et al., 1989). The (mostly abandoned) channel belts and sub-lobes can be grouped into three generations, according to relative age judging from morphological appearance.

The channel belts and sub-lobes of the oldest generation are visible in the satellite images at various places within the active lobe (Figure 2.7). Morphologically, these old channel belts already become poorly defined and start to blend into the surrounding floodplain by ongoing sedimentation from presently active channels. Nevertheless, their subtle relief may play an important role in guiding new avulsions.

A number of avulsions near the apex of the active lobe took place in this early phase of lobe development that seems to have overlapped with the period of formation of the fan lobe north of the present active lobe. In the apex area, old river courses with bends that roughly have the dimensions of present Taquari bends can be observed on the satellite images north and south of the present Taquari. An abandoned channel belt that parallels the Taquari a few km's to the north in the Caronal area, probably belongs to this oldest generation of channel belts. The alluvial ridge of this channel belt formed a barrier for floodwaters associated with the recent Caronal avulsion (see below), routing them westward. A few big abandoned channel belts with two associated sub-lobes can be observed south of the present Taquari. These channel belts resulted from south-westward avulsions near the fan-lobe apex. Recently, reaches of these old systems were reactivated by crevassing of the left levee of the Taquari, little upstream of the Caronal avulsion.

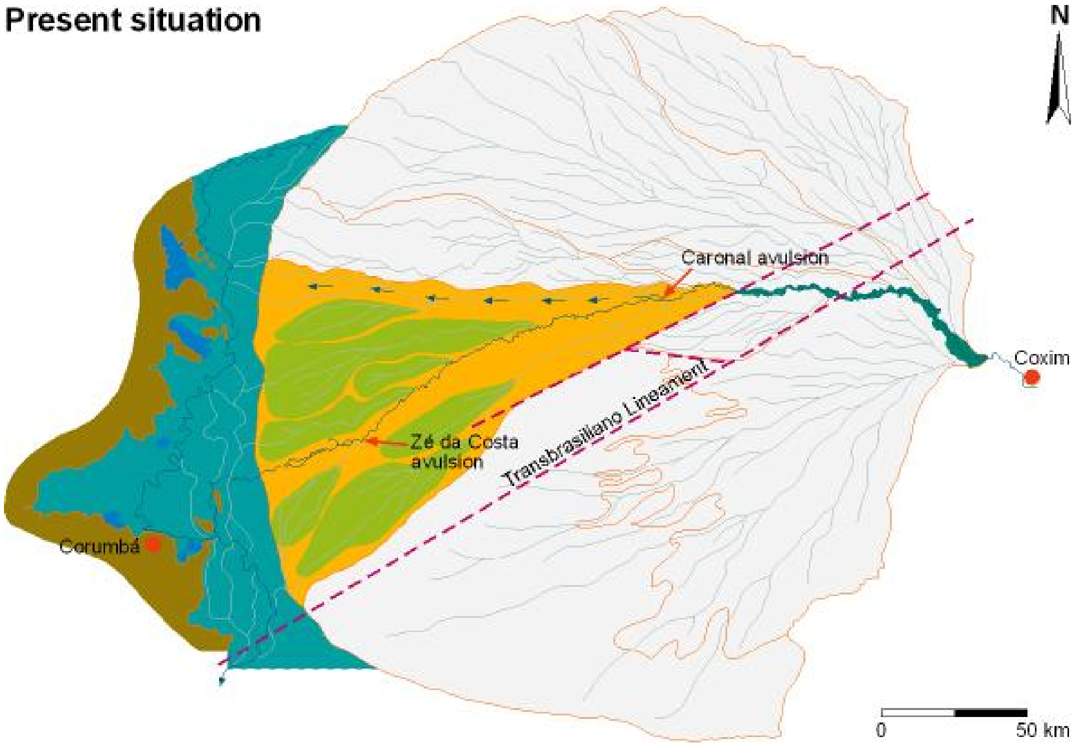

Figure 2.9 The most important avulsion presently going on is the Caronal avulsion. The flow path of this avulsion is steep and energetically favourable because it is not obstructed by recent sub-lobes. A new sub-lobe associated with the recent Zé da Costa avulsion will fill the space between previous sub-lobes on the lower fan.

A big avulsion near the lobe apex led to establishment of the present middle-fan reach of the Taquari (Figure 2.8). Three sub-lobes were deposited downstream and still stand out very clearly on recent satellite images. A fourth sub-lobe developed subsequently more to the south. Minor avulsions took place within this sub-lobe that was active during the past 40 years (Padovani et al., 2001) and maybe longer.

The westward shift of the Paraguay River to the Corumbá area may have been related to a rise in flood basin water levels east of the river, due to increased discharge through the present active lobe. Likewise the Cuiabá River in the north of the study area is hypothesized to have avulsed westward at an earlier stage, when the lobe north of the present active lobe developed (Figure 2.7). The new course of the Paraguay River crosses the abandoned old Paraguay channel belts east of Corumbá and probably linked up with a lower course of the Taquari.

Presently, new avulsions are taking place in two areas (Figure 2.9). In the middle-fan area, near the apex of the present active fan lobe, the so-called 'Caronal avulsion' is going on. On satellite images and aerial photos it can be seen that the avulsion route is guided by an abandoned channel belt. Near the avulsion point the positive relief of the old levees forces the Caronal avulsion path westward. More downstream, the avulsive floodwaters follow reaches of the abandoned channels. In the fan-toe area the flow path is determined by a relatively low area between the previous fan lobe and an old sub-lobe. The straight unobstructed flow path to the Paraguay River seems very efficient, geomorphologically, which probably explains that the avulsion has rapidly developed since 1979 (the year of its initiation, according to a local farmer). The existing channel of the Taquari downstream of the avulsion point is rapidly silting up. The channel shallows but also narrows, being laterally invaded by vegetated side benches. This phenomenon is known from other rivers that are abandoned after avulsion (Makaske et al., 2002). Several crevasses recently developed on the left bank of the Taquari River in the Caronal area (Figure 2.10).

Figure 2.10 A small crevasse in the natural levee of the Taquari River, which could develop into an avulsion. Note the remains of sandbags that were used to close this gap.

In the fan-toe area, the Zé da Costa avulsion has started around 1988 (Assine, in prep.). This avulsion is virtually completed now, in the sense that the old Taquari channel immediately downstream of the avulsion point is totally plugged by sand. The avulsion belt, however, is still rapidly evolving. Lack of levees and channel confinement presently typify this area. This new reach of the Taquari strongly anastomoses in extensive wetlands. Sub-lobe development has just started. In the future, a new sub-lobe will fill up a gap between previous sub-lobes on the lower fan.

The recent avulsions have severe impact on the traditional economic activities in the area. Previous major avulsions that affected large areas, like the Caronal avulsion does nowadays, maybe happened too long ago to be part of the collective memory of the local population. Therefore, in the perception of the local population the recent avulsions represent a sudden, unexpected and dramatic change of the river system.

The above described reconstruction of Taquari avulsion history, however, demonstrates that the recent avulsions logically fit into the natural pattern of channel shifting on the Taquari alluvial fan that has been ruling the geomorphological evolution of this area for many millennia.

2.5 The locations, timing and causes of the recent avulsions

It seems that most of the flooding and sedimentation problems in the area are the result of the recent avulsions. Although it has been shown that avulsion in general is a basic element of natural alluvial fan dynamics, the exact locations, the timing and the causes of the recent avulsions of the Taquari still need clarification, in order to evaluate potential control measures.

Most avulsions are the result of sedimentation. In natural river systems, sedimentation on the bed and banks of a river is much more rapid than further away from the channel on the floodplain. As a result the channel belt gradually becomes elevated on an alluvial ridge above the surrounding floodplain. After a long period of sedimentation the slope across the natural levee to the floodplain has become much steeper than the channel slope. At this stage the river becomes liable to avulsion: i.e. it is close to the avulsion threshold. The preparation of the river and the floodplain for avulsion is a slow geological process. Although the river seems stable during this process, in fact it is gradually moving towards critical conditions. When critical conditions are reached, a trigger is needed to initiate avulsion. Often an extreme flood is an avulsion trigger, although all kinds of temporary obstructions (such as log and ice jams) may also act as triggers (e.g. Jones & Schumm, 1999; Makaske, 2001). It is important to note that a trigger alone is not enough to cause avulsion. Floodplain conditions need to be favourable due to the long-term geological processes that shape the floodplain.

In the case of the Zé da Costa and Caronal avulsions, the development of critical conditions can be satisfactorily explained by natural alluvial fan processes. However, the trigger that caused the Caronal avulsion seems to have been slightly different from the one that initiated the Zé da Costa avulsion. The Caronal avulsion was most likely triggered by extreme floods from the upper Taquari catchment. Higher flood levels of the Taquari since the early 1970s are likely to be due to climatic change (Galdino et al., 1997; Garcia & Vargas, 1998; Collischonn et al., 2001). Increased peak discharges could not be accommodated by the present Taquari bed. Confinement of the Taquari floodplain on the upper fan (Figure 2.11) inhibits avulsion. Avulsion took place at the first suitable location downstream of the point where the floodplain widens, in the apex area of the present active fan lobe. This avulsion location confirms upstream control of the Caronal avulsion.

The exact location of the Caronal avulsion point may be related to the local composition of the subsurface. Comparison of the Taquari channel planform (from 1998 LANDSAT image) with the channel planform on air photos from 1966 indicates rapid lateral migration (Figure 2.12). This may be due to an easily erodible sandy substratum. In this context it is interesting to note that an important abandoned channel belt flanks and partly underlies this reach of the present Taquari channel belt. Channel-belt deposits are much sandier than floodplain deposits. Rapid lateral erosion of natural levees tends to create low spots in the banks that are suitable avulsion points.

Figure 2.11 Upper-fan entrenchment of the Taquari. Four-metres-high cut-bank exposes deposits of an abandoned fan lobe.

A boring in the Taquari levee next to the entrance of main Caronal avulsion channel revealed sandy deposits (fine and medium sand) below a 1.7-m-thick package of predominantly sandy and silty clay. The sandy deposits are interpreted as channel deposits of the present Taquari. Four radiocarbon dates of wood fragments from the upper clayey beds yielded 'modern' ages between 1959 and 1960 AD (calibration results between 1980 and 1986 AD for two dates are rejected because of geological inconsistency). In a boring in the Taquari levee near Porto Mangueira, 15 km downstream, a comparable succession was encountered. Two radiocarbon dates of wood fragments from the upper clay package also yielded 'modern' ages between 1954 and 1972. These results confirm strong lateral activity and rapid sedimentation (19-36 mm/year) within this reach of the Taquari channel belt. Caution should be taken, however, with the interpretation of these 'modern' (post-1950 AD) radiocarbon dates. It should also be stressed that these sedimentation rates apply to a local situation and may not be representative for average levee aggradation rates. Although some doubts on their interpretation remain, the calculated sedimentation rates can be classified as very high.

Strong increase in floodplain sedimentation on the Taquari since the 1970s was reported by Godoy et al. (1998, 2002) and Padovani et al. (1998b) based on ^{210}Pb dating of lake sediments related to deforestation and other human activities in the Taquari catchment. On the incised part of the Taquari on the upper fan and in the apex area of the present active lobe (upstream of the Caronal avulsion), up to 80-cm-thick sand beds were observed on top of clayey levees, during the field survey carried out for this study. These beds probably relate to the recent increase in activity of the system. It is important to note that as far as overbank sedimentation is concerned, the effects of a climatic change, can not be separated from the effects of increased sediment production in the catchment, due to human activities. Increased discharge in response to climatic change leads to increased overbank flooding, which in turn may cause increased overbank sedimentation, also if sediment delivery remains constant. As to in-channel sedimentation it should be stressed that increased sediment delivery from the catchment does not necessarily imply increased in-channel sedimentation, since the bulk of Taquari bed load consists of fine sand that can easily be transported in suspension with increased peak discharges, as long as the maximum sediment transporting capacity is not reached, which is usually the case. An increase in sediment transport [as suggested by Padovani et al. (1998a)], therefore does not automatically mean an increase in in-channel sedimentation that could invoke overbank flooding and avulsions. All in all, the cause-and-effect relationships between sediment production in the catchment, sediment transport under changing discharge regimes (due to climatic change) and sedimentation on the alluvial fan, are much too complicated to assume a straightforward relationship between the recent avulsions and human activities causing erosion in the catchment, as proposed by Assine & Soares (1997, 2004). Especially with respect to the Caronal avulsion, the timing (start around 1979) also indicates that critical conditions already were reached prior to major developments in the catchment in the 1970s. To reach critical conditions for avulsion substantial sedimentation is needed. Even with rapid sedimentation much more time would have been needed than the few years between the early 1970s and 1979. It rather seems that increased peak discharges since the early 1970s directly triggered the avulsion, with already existing favourable floodplain conditions that have evolved during the preceding centuries.

The Zé da Costa avulsion originated in a different way. On the lower alluvial fan backwater effects from the Paraguay River are likely to play an important role in triggering avulsions. A comparison of 1966 air photos and a 1998 LANDSAT image shows that lateral channel activity did not play a significant role in the initiation of this avulsion, contrary to the Caronal avulsion. The channel shows virtually no lateral changes around the avulsion point over the period 1966-1998 (Figure 2.12). The composition of the substratum may have contributed to lateral channel stability of this reach. In a boring on the natural levee of the Taquari at Porto Rolon, 20km upstream of the avulsion point, a 1-m-thick stiff strongly consolidated package of silty and sandy clay was encountered below a 1.8-m-thick package of much softer silty and sandy clay, with intercalated beds of fine sand. The boundary between both units is sharp. The strongly consolidated deposits are interpreted to belong to an ancient fan lobe underlying the present active lobe. The top of the ancient lobe has undergone long weathering and soil formation. The base of the Taquari channel has scoured into these stiff deposits that allow very limited lateral migration of the channel. Two radiocarbon dates of wood and leaf fragments from near the base of the upper unit yielded 'modern' ages between 1962 and 1972 AD (calibration result 1980-1981 AD for one date is rejected because of geological inconsistency). Sedimentation rates based on these dates are very high (36-47 mm/year).

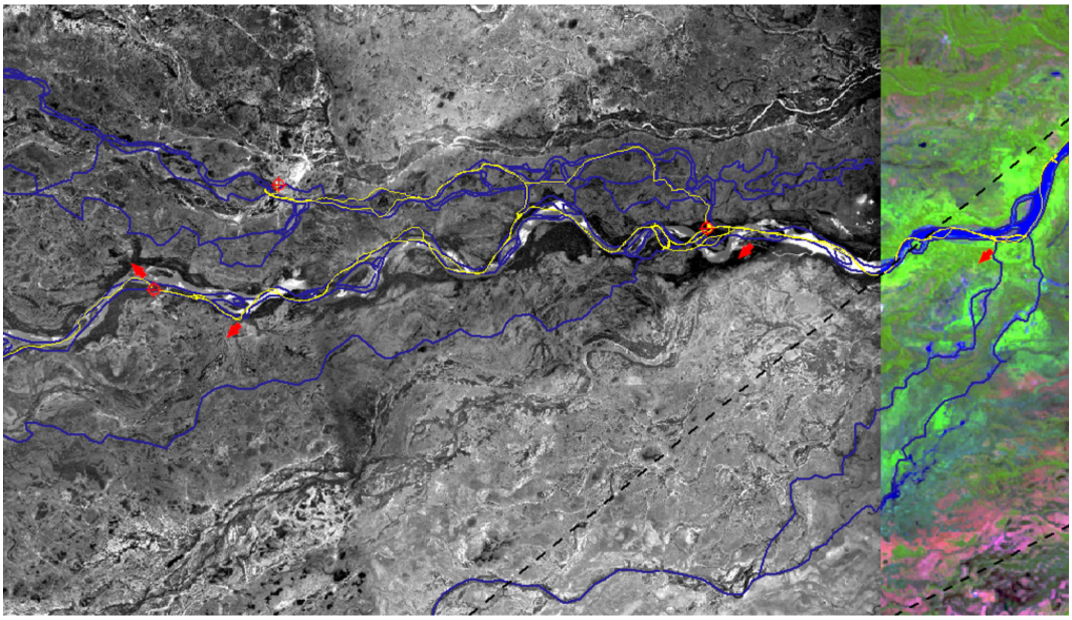

Figure 2.12 Comparison of Taquari channel planforms on 1966 air photos (black and white) and 1998 LANDSAT image (colour). Recent channels from the LANDSAT image are projected in blue on the air photo mosaic. The channel has laterally migrated considerably. The main Caronal avulsion point is indicated by a red circle (right-centre). Red arrows indicate abandoned channel belts. Yellow lines indicate the route surveyed in April 2004. Note small recent crevasses in the south bank of the Taquari. Area shown is ~62 km wide; north is up. (Source: B. Maathuis, ITC).

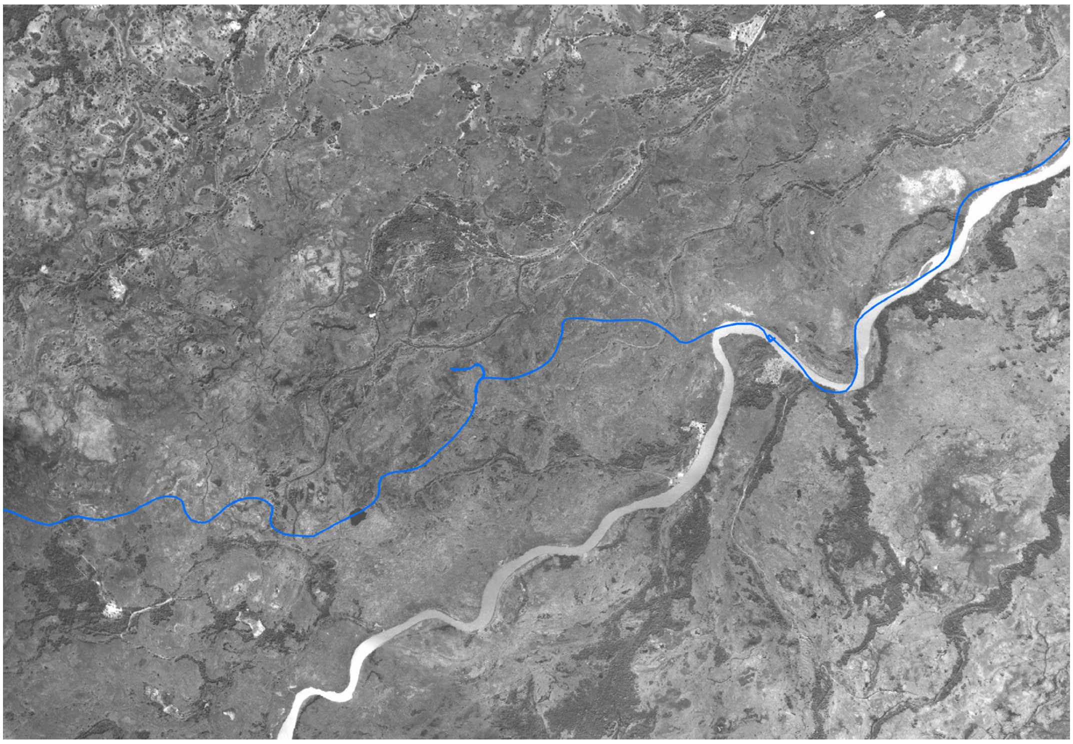

Figure 2.13 The route surveyed in April 2004 projected on the 1966 air photos of the Zé da Costa avulsion area. Lateral channel migration was insignificant (slight differences may also have been caused by small errors in georeferencing). The Zé da Costa avulsion site is where the surveyed route abruptly leaves the 1966 channel. Area shown is ~10km wide; north is up.

The Zé da Costa avulsion occurred at a logical spot: a sharp outer bend of the river where erosive power of the flow is highest. Whereas the Caronal avulsion flow path is strongly influenced by pre-existing topography, (it parallels and reactivates abandoned channels), the Zé da Costa avulsion route obliquely crosses a number of abandoned channels and seems more or less unrelated to previous topography. This is interpreted to result from the different avulsion mechanism. High flood levels on the Paraguay River floodplain cause backing up of water in the lower course of the Taquari, especially when floods in both rivers coincide (which is usually not the case, but it may occur) (see also chapter 5). This may trigger avulsion and, after initiation, contributes to rapid further development of an avulsion. When backwater effects cause extensive flooding of the fan-toe area, local water gradients and consequently water flow become more or less detached from underlying local floodplain topography. Since the early 1970s, average annual Paraguay River flood levels have risen more than 3 m, with respect to average flood levels during the 1960s (Galdino et al., 1997). Having been initiated in 1988, since then, backwater effects are supposed to have strongly contributed to the relatively rapid development of the Zé da Costa avulsion.

2.6 Conclusions and recommendations

1. Avulsion is a key process in the long-term geomorphological evolution of the study area. It is inherent in the natural dynamics of low-gradient floodplains (Paraguay River) and alluvial fans (Taquari River).
2. The present flooding and sedimentation problems in the area are strongly associated with recent avulsion activity that concentrates in two areas: on the upper part of the presently active fan lobe (Caronal area), and on the fan toe (Zé da Costa area).
3. Long-term sedimentation processes have created the necessary conditions for the recent avulsions. This means that energetically favourable alternative flow paths for floodwaters have developed on the fan.
4. Starting from critical conditions, the Caronal avulsion was most likely triggered by several extreme floods from the upper Taquari catchment, which seem to have been caused by climatic change.
5. The Zé da Costa avulsion is probably controlled by backwater effects, with high Paraguay River flood levels raising Taquari water levels over the fan-toe area. Average annual Paraguay River flood levels have strongly risen in the early 1970s after a period of low discharges and have remained high since then.
6. There are indications of a recent increase in overbank sedimentation on the Taquari alluvial fan. Whether this potential increase in sedimentation is caused by human activities in the Taquari catchment is unclear. Increased floodplain sedimentation, if true, probably has not significantly contributed to the recent avulsions.
7. Because of the existence of alternative flow paths that are energetically more favourable than the present Taquari channel, the recent avulsions can hardly be arrested. Local measures such as closing the entrance of an avulsion channel are not sustainable, because critical conditions exist not only at the avulsion point

but extend along the channel for considerable distance upstream and downstream of the avulsion point. Rapid lateral channel migration and a sandy subsurface (facilitating erosion and groundwater seepage) further complicate technical measures, especially in the Caronal area.

8. Measures in the upper catchment will most effectively prevent excessive flooding on the Taquari alluvial fan. It may be expected, however, that reservoirs for retention of floodwaters will rapidly fill up with sediments, given the high sediment production of the catchment. Seepage through the permeable sandstone underlying the reservoirs may be another problem.
9. Although sometimes seen as harmful for the Pantanal ecosystem, the long-term effects of avulsions for the area as a whole are probably favourable. Recurrent avulsions rejuvenate vegetations, create landscape diversity and thereby contribute to biodiversity.
10. Further research of the geomorphological evolution of the study area should focus on the collection of geochronometric data, to gain more insight into the spatial variability of sedimentation rates on the Taquari fan and the timescales of lobe and sub-lobe evolution.

3 The Digital Elevation Model

Dr B. Maathuis[5]

3.1 Introduction.

The overall objective of this project is to support the wise use of the plains of the Pantanal Taquari river catchment by developing tools for decision making in river management at the catchment basis. With regard to this two problems are of main importance, the first: the development of a river flow and sedimentation model of the lower Taquari in the Pantanal and improve the Brazilian knowledge in this matter. Second is the capacity building for the organization of integrated river management at the catchment level including all relevant stakeholders. This report mainly focuses on the first problem identified and describes those aspects that have contractually been assigned to ITC. In this respect, apart from participation in relevant project activities, the main focus was on the preparation of a digital terrain model (DEM) to facilitate further hydro-dynamic modelling by other partners.

The main activities have been:

1. Remote sensing data collection, initial analysis and preparation of presentation.
2. Participation in the 1st workshop on the Taquari-Pantanal Project, Corumbá, 19-20 August 2003. A presentation was given entitled: Remote sensing image analysis and altitude determination of Rio Taquari-Pantanal system.
3. Additional data collection and short field survey directly after the 1st workshop.
4. Attending 2 project meetings (coordinating the Dutch partner effort) at Alterra in Wageningen and giving a presentation of ongoing activities entitled: SRTM-derived DEM: Optimization for hydrologic modelling.
5. Participating in a joint fieldwork in April 2004 to collect additional data on the Taquari river from Coxim to Corumbá using several techniques.
6. Processing the collected data and presenting the obtained results in a presentation at Alterra entitled: Pantanal Digital Terrain Model.
7. Disseminating the processed data to Alterra.
8. Preparation of a poster presentation showing the obtained results for the closing workshop in Corumbá.

In house activities consisted of:

1. Testing of specially developed software routines for DEM hydro-processing.
2. Acquire dedicated DEM filtering software and processing the Pantanal DEM through different model runs with different parameter settings.
3. Supervising MSc study related to Hydro-DEM processing.
4. Integration of sounding-surveys and GIS.
5. Single dual frequency geodetic (D)GPS recording and post-processing procedure development applicable to the Pantanal field conditions.

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3.2 Data collection and processing

Prior to the first workshop most attention was given to the collection of available data in maps, reports, remote sensing data and elevation data.

Remote sensing data
An inventory was made of available remote sensing data of the Pantanal region as well as elevation information. This was done using international archives as well as the in-house available digital archive (Geo-data warehouse) and analogue archive. This resulted in a large amount of remote sensing images, available from different sensors from 1973 onwards, such as Landsat-MSS and TM, Aster, JERS. Furthermore some aerial photos from the analogue archive were available (covering small portions of the Paraguai river floodplain).
Details are as follows:

- Landsat MSS data from 15 and 16 March 1973.
- Landsat TM images from 1986 till 1989, dry season conditions. Excellent quality, whole Taquari catchment at 30m. spatial resolution, 7 spectral bands. Total of 11 scenes. A mosaic of 9 scenes is covering the lower Taquari and 4 scenes cover the upper Taquari catchment.
- Aster (onboard of EOS AM-1) images from 2000 till beginning of 2003, dry season conditions, partly cloud covered; only covering the lower Taquari. Visible and near infrared images at 15 m. spatial resolution, 3 spectral bands. 95 scenes are available; a mosaic has been made from 25 selected scenes.
- JERS (radar L-band, 23 cm centre wavelength, HH polarization): mosaic of February 1997, showing wet season conditions, resampled to 100m. spatial resolution, mosaic from 50 JERS-1 scenes.

As the Pantanal region is very extensive only a mosaic consisting of several individual images can cover the whole area. Given the revisit time of these medium resolution satellites, coupled with occurrences of clouds, a mosaic can only be constructed from images acquired over a longer period of time. Therefore the flooding phenomena depicted on the individual images differ strongly. The JERS data are acquired within a specific period, but the spatial resolution to which the mosaic is resampled makes it less useful.

Maps and reports
Some 1:50.000 scale maps covering part of the Paraguay floodplain region, next to general small scale maps, were obtained. Also some relevant older reports of the Pantanal area could be obtained.

Elevation data
Apart from the GTOPO30 (30 arc-second DEM, roughly 1 km spatial resolution) the elevation data that could be acquired of the whole region is from the Shuttle Radar Topographic Mission (SRTM) of February 2000. Data are collected from the space shuttle Endeavour which was launched on 11 February 2000, during an 11 days mission from an orbital altitude of 233 km using a modified radar instrument called the Spaceborne Radar Laboratory, with an Interferometric Synthetic Aperture

Radar (IFSAR), two C-band antenna's (centre wavelength 5,3 cm), one of which was mounted on a 60m. mast, the other was situated in the cargo bay. The SRTM swaths extended from about 30 degrees off-nadir to about 58 degrees. The spatial resolution available is 90m (3-arc-seconds at equator is 90m), which is downsampled using a 3 by 3 averaging filter algorithm from the original 30m. resolution data (1 arc-second). Since the primary error source in the elevation data has the characteristics of random noise, this reduces that error by roughly a factor of three. The vertical resolution is 1 m. having an absolute accuracy of better than 16 m (90 % confidence level). Data are processed in one degree by one degree cells. In order to cover the Taquari catchment a mosaic was constructed of 40 tiles, covering an area from 16 degree South / 59 degree West (upper left corner) to 21 degree South / 53 degree West (lower right corner). More details on processing of the DEM are provided below.

Data collected at Embrapa in August 2003

After the 1st workshop at the Embrapa office in Corumbá the following data could be obtained:

Satellite data:

- SAC-C images from 08 Aug '01, 04 March '02, 28 September '02 and 24 April '02. This sensors spectral resolution of the 5 bands is identical to Landsat TM, spatial resolution is 180m.
- A mosaic of Landsat TM, representing the dry season conditions as of 1998-1999, transformed to a pseudo natural colour, in 30m. and 180m. resolutions (VNIR-R-G transformed to RGB).

GIS data:

- Scanned topographical maps 1:250.000.
- Collection of GIS data based on the 1:100.000 scale topographical maps in a data format that can be accessed by the software SPRINGS.
- A collection of exported files from SPRINGS in an ARC-shape file format.

Next to this, during the one day field visit, field photos were collected as well as site observations.

3.3 SRTM Digital Elevation Model processing

Upper Taquari catchment- the Plateau (Planalto)

First the quality of the SRTM elevation data was evaluated using the Taquari catchment area upstream of Coxim. Small data voids (e.g. along some portions of very steep, nearly vertical escarpments) were linear interpolated. In general no further correction was adopted as the area was properly recorded and is having substantial elevation differences. Apart from this the area is extensively used for agriculture and cattle ranging, some small regions are covered by natural open savannah vegetation. Only along the escarpments a dense forest cover is situated. Given the type of land use and cropping patterns for the area in relation to the date of acquisition and the nature of interaction at the surface given the wavelength used of the active radar signal to collect the elevation information it was assumed that for major portions of the upper catchment region the elevation data is representing the actual ground levels. To extract relevant hydrological parameters the elevation data was processed using different software packages and extensions such as:

- ARCVIEW HEC- GeoHMS extension;
- ARCGIS Hydro-tools extension and Taudem extension;
- DiGeM (dedicated free software tool for digital terrain analysis);
- At a later stage the ILWIS Hydro-tools module (self developed software tools for DEM processing).

Especially the ARCGIS-Taudem extension facilitated the processing and extraction of hydrological parameters, such as river network and (sub) catchments of good quality next to the more generic variables as slope and aspect. Visually the results could be compared to available satellite images and the drainage lines extracted were superimposed on these images. DiGeM allowed for the calculation of a number of compound terrain parameters such as (1) the Wetness index (catchment area/slope gradient) showing the spatial distribution of zones of saturation and variable sources of runoff generation, (2) Stream Power index (catchment area*slope) showing areas susceptible to concentrated surface runoff and (3) LS or Transport index accounting for the effect of topography on erosion (using catchment area instead of the one-dimensional slope factor as in the USLE). Also the first test runs were conducted with the ILWIS hydro-tools module, showing similar results as with the Taudem extension. The information obtained, together with satellite data, is useful in the analysis of upstream-downstream relationships envisaged by the other project team members.

Lower Taquari river - the Pantanal

Using the same procedures the raw SRTM data was processed of the lower Taquari reach. Given the completely different terrain characteristics (from Coxim the Taquari traverses an alluvial fan complex before it enters into the wetlands - marshes) these initial results were not successful. This was basically due to two reasons: (1) the strong influence of the reflectivity – backscatter of the radar signal by the top of the natural vegetation and (2) due to the fact that the radar signal does not penetrate water, so therefore no bathymetric information, extremely important for the lower Pantanal region, was incorporated in the data source.

Prior to the field survey, in order to see how the SRTM data could be modified a DEM optimization routine was developed and tested. The routine is consisting of several steps:

- In order to remove the effect of vegetation the SAC-C image of 8 Aug 2001 (bands 3 and 4) was selected and a Normalized Difference Vegetation Index (NDVI) was calculated. It was assumed that higher NDVI values were corresponding to higher vegetation structures, like bushes and trees. The NDVI map was reclassified into elevation classes and subsequently subtracted from the initial DEM.
- To incorporate the bathymetric information of the extensive drainage network existing in the Pantanal a drainage network layer, taken from the 1:100.000 scale topographical maps by Embrapa was used. This drainage map was corrected and

updated (especially along map boundaries) using the pseudo natural colour mosaic also obtained from Embrapa. The corrected drainage system was reclassified into three classes, representing the Paraguay river, the Taquari river and the other drainage network. Different values are used to represent the width and depth of these rivers. The DEM corrected for vegetation influence was modified once more to represent the drainage network as well. In order to obtain a consistent flow direction and accumulation network the drainage was incised with values over representing the actual river depth. In a subsequent step the differences (reclassified into a number of classes) between the original DEM and the drainage incised DEM was used to raise the actual riverbed levels. The then newly computed flow direction and flow accumulation resulted in a hydrological sound drainage network when compared to the network as it is depicted on the satellite images

- Last but not least a multi-temporal classification of all 4 SAC-C images was conducted and a flood extent map was produced, showing the areas continuously flooded up to occasional flooded and non flood affected. Apart from the river system, based on the flood frequency a depth value was assigned and this was once more used to correct the DEM

These three steps in this order completed the initial DEM correction procedure. The main problems encountered during this process were:

- NDVI is not a good representation of vegetation, also areas covered with e.g. dense grass, water hyacinth produce high NDVI values.
- Visual interpretation of the drainage network from the satellite images is very difficult for the lower Pantanal region, small diversions and avulsions are not well depicted. Furthermore the drainage network was not recorded at bank full stage.
- Information with regard to bathymetry was not available and was assumed. Even after raising the river bed levels these were still considered too deep. Also the values used for correction of flood affected areas were assumed.
- Sequence of DEM correction is important because sink-fill operators, prior to the flow direction and flow accumulation computation affect the results.
- The modified DEM at this stage could only be validated in a relative way as no absolute elevation information (X,Y,Z) was available in the used ellipsoid and datum and transformation parameters were unknown.

Therefore the results had a preliminary character and had to be further validated during a planned field campaign.

Field campaign April 2004

From 28 March till 9 April 2004 a field campaign to collect additional information was conducted. The objectives of field survey have been:

- Study of the main morphological characteristics of the Taquari river and active floodplain from Coxim to Corumbá and collect relevant info for hydro model input.

– Collect relevant field information to correct the Shuttle Radar Topographic Mission Interferometric derived Digital Surface Model (DSM) to be able to convert it to a realistic Digital Terrain Model (DEM) of the Pantanal region.
– Study the terrain features surrounding the river and active floodplain into more detail, especially along the main avulsions, the Caronal and Zé da Costa avulsions.
– Collect multi temporal aerial and satellite image info for change analysis along the sections affected by avulsions.

Equipment used for survey was:
– Leica SR530, RTK (D)GPS and antenna
– Garmin Fishfinder – transducer (sonar) and Garmin GPS 72
– Garmin Etrex GPS
– Laptop (Erdas Imagine, ArcGIS, Arcview, ILWIS, Leica-SKI-Pro and Gartrip) and a palmtop (Ipaq with ArcPad)

The following data were collected:
1. Sounding and GPS information along the river, the whole section, from Coxim to Corumbá, water depth, height and X,Y (UTM, zone 21, WGS84) information, longitudinal profile, 1 point per 10 seconds (approximately 1 point per 80metres), covering main bed configuration changes within the river and cross-sections, 1 point per 2 seconds (approximately 1 point per 2,5 metres).
2. DGPS measurements, 6 points along the Taquari, 2 along the Paraquay Mirin, a point at Corumbá harbour, 2 observations on geodetic points at University of Corumbá, one from the aviation authority and one from the Department of Geodesy, Brazil (IBGE). Time duration per point between 1½ to 2 hours of continuous recording. Data converted to RINEX format for later post processing at SOPAC-SCOUT. Also a geodetic point at ITC was measured for quality control.
3. Sediment samples taken from the river bed using sediment grabber along cross-sections and flow velocities and visual observations for the whole duration of the boat trip (7 days).

All data collected by sounder, (D)GPS were downloaded and pre-processed successfully and exported as Arcview Shape files. The measurements need to be corrected for sounder depth offset (+ 30cm) and GPS height offset (-60cm). General overview of data collected is presented in Figure 3,1 (total river length covered: >400km). Sediment samples (17) are given to the laboratory of Embrapa for grain size analysis. Further details are presented below.

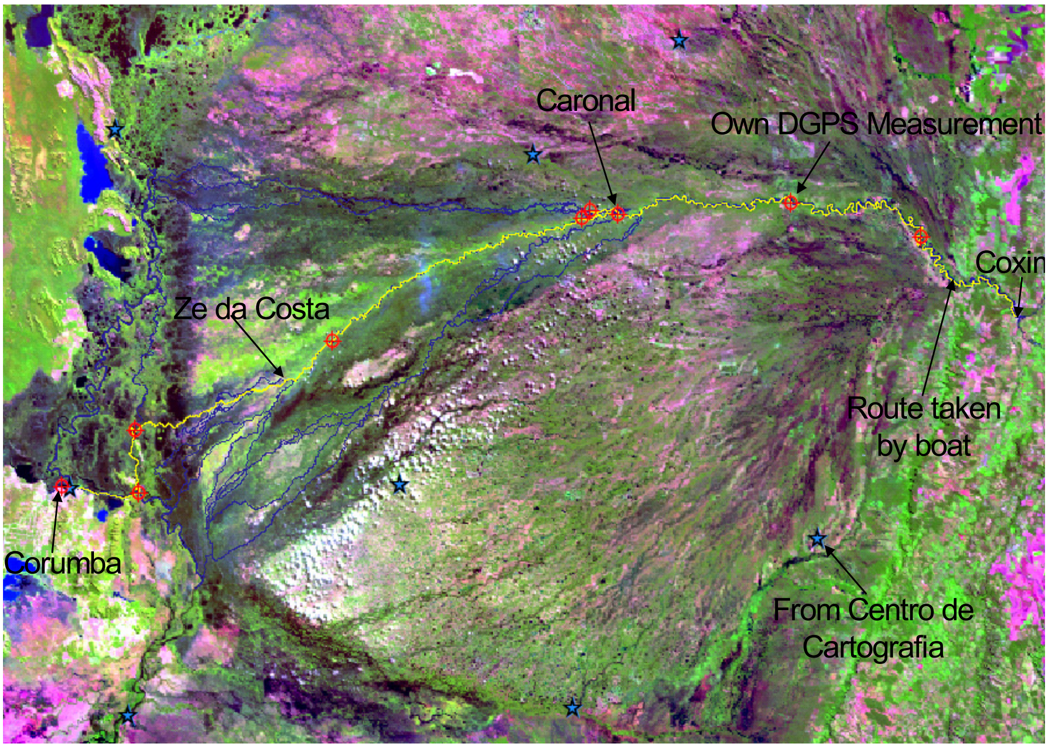


Figure 3.1. Track record and (measured – obtained) DGPS locations along the Taquari.

When plotting all data on pseudo natural colour composite Landsat TM background (UTM, zone 21, WGS-84 ellipsoid and datum) there is a good overall match.

Other data collected at Embrapa: Landsat ETM images of 04-05-2000 and 29-09-2000 (WRS 227-73 and 226-73), all bands, Aerial photographs (panchromatic, April 1960), recorded in 1960 of the two avulsion areas, scale 1:60.000, corresponding topographic maps of these areas of interest. Furthermore the GPS tracklog of Embrapa was downloaded and converted to Arcview Shapefiles and integrated together with the preliminary DGPS observations, sounding point and track-log files.

3.4 Analysis of collected data

Sounding measurements

In order to get a better idea of the Taquari, during the trip from Coxim to Corumbá, a transducer – sonar was attached to the back of the boat, about 30cm below the water level. Water depths are registered using this portable sounder connected to a GPS. The sounder uses a single frequency transductor of 200kHz to measure the distance from the sensor to the river bed with an accuracy of 10cm. Minimum recording depth of the water body is 60cm. Furthermore if there is a high suspended sediment concentration the sounder is not able to take measurements. Most of the cross sectional locations selected had been measured previously by other organizations. Additional cross-sections are selected based on hydro-dynamic model requirements. Horizontal accuracy is depending on the quality of the GPS receiver used, which in this case is in the order of 5 to 10m. All collected data are transferred from the GPS to the laptop in the field and pre-processed in a GIS (ILWIS) twice a day. The point and track records were integrated with a geocoded satellite image to check the locational consistency of the measurements. At a later stage the data was transformed into a different format in order to be compatible with software packages used by other project partners for further post-processing and analysis.

DGPS measurements

To get an idea of the absolute vertical accuracy of the DEM dual frequency geodetic DGPS static measurements were conducted at several locations along the Taquari. Given the type of survey it was not possible to prepare a base and a rover station for real time accurate position measurements as (1) setting up a base station requires long duration measurements and (2) the distance between the base station and rover is restricted. There is a limiting distance with regard to the radio link between the two stations (no mobile telecommunication network is available in the Pantanal) and with increasing distance (over 10km) from the base station problems can occur when trying to resolve the ambiguity (N). To overcome this problem also long measurements are needed and measurements become less representative causing larger positional errors, especially vertically (accuracy drops with 1 mm / km). Another possibility, through collection of correction factors using satellite communication by OmniSTAR, was thought to be not accurate enough as the ground stations situated along the coast (Buenos Aires, Curitiba, Rio de Janeiro and Vitoria (for which the correction factors are computed - known) are less representative for the Pantanal region causing at best absolute vertical accuracies in the order of 30 to 50cm. Therefore use was made of a free Internet GPS post-processing service provided by the Scripps Orbit and Permanent Array Center (SOPAC). This centre provides precise, rapid, ultra rapid and hourly orbits for the International GPS Service (IGS). The IGS network is consisting of over 200 permanent GPS stations and the three nearest stations are used by the Scrippt Coordinate Update Tool (SCOUT) to process the dual frequency geodetic quality GPS RINEX (Receiver Independent Format file) data observed in static mode and receive rapid turn-around precise coordinates. Solution quality depends largely on the availability and proximity (also called base line) of the nearest three base station data and the availability of precise satellite orbits and clock corrections.

To validate the post-processing results two known geodetic points were recorded, next to those in the Pantanal, one point in Enschede, the Netherlands and one in Corumbá, Brazil. This resulted in height differences of 2,5cm (average base line of 130km) and 11cm (average base line of 1160km) for Enschede and Corumbá respectively. Given the fact that the average base line length is roughly the same for the other measurements and the duration of measurements was mostly longer than the measurement at the geodetic point in Corumbá, the obtained vertical accuracy (in the order of 10cm) is thought to be representative for the other static dual frequency measurements conducted in the Pantanal.

Other measurements and observations

Other activities conducted during the boat trip included collection of sediment samples taken at locations were cross sections were recorded. At these locations also flow velocities were recorded using the GPS. Furthermore visual observations, to get a better idea of the (changes in) landscape were performed and flood marks were observed.

The main river system differences observed are:

- From Coxim till approximately 30km east of the Caronal avulsion. The Taquari incised the fan surface, is confined to a narrow active floodplain, with levees of about 60cm in height given the actual water levels during the survey. The vertical escarpments mark the boundary between the floodplain and the fan due to active undercutting of the river. The difference between the fan surface and the river level is in the order of 5 to 6m. at the entrance of the Taquari into the Pantanal. This difference in elevation is decreasing towards the west and the fan surface disappears gradually. The average longitudinal slope is in the order of 30cm / km and the river depth in general is exceeding 2,5m. Furthermore the river width in general is greater than 300m. The river has a strong meandering pattern and especially in the outer bends is showing frequent signs of active bank erosion. Many cut-off meanders exist in this river reach. The flood marks observed show that only the active floodplain is flood affected. Flood marks are observed at 1,2 to 1,5m. above the water level. Flow velocities generally exceed 4-5 km/hr and the river is carrying suspended sediments. The maximum water levels do not reach the fan surface.
- The reach 30km east of the Caronal avulsion till approximately the Ze da Costa avulsion. Here the river is not incised any more. The levees are in the order of 30cm above the water level. Hardly any signs of river bank (lateral) erosion. The width of the Taquari decreased to less than 200m. The river depth is in general less than 2m. The longitudinal slope in this reach is between 20 to 30cm/km. The meandering pattern has disappeared and the river has become straighter and is showing a more braided appearance with many bars and shallows. In the upper part of this reach a number of avulsions exist, both on the left and right banks of the river, diverting a substantial amount of the river's discharge. Flow velocities are less, 2,5 to 4km/hr but still suspended sediments are transported. In general flood marks are situated 10 to 20cm above the levee surface adjacent the river indicating that large regions are flood affected during high river stage.
- Downstream the Ze da Costa avulsion. Here the longitudinal gradient becomes very gentle; about 10cm/km. Large lakes are present in this area and given the stage fluctuations of the Paraguay River combined with the small topographic differences the area will be affected by backwater effects from this river. The more anastomosing pattern of the fluvial system in this reach might be attributed to this. Flow velocities recorded during the survey are in the order of 1- 2km/hr. In general the surveyed reach is having river depths of over 3m. The amount of suspended sediment has gradually disappeared. Further downstream fossil Paraguay levees are found as well as some older structural outcrops – low hills. Apart from these slightly higher elevated areas the region is prone to extensive flooding

With regard to land use and vegetation the following observations can be made:
Stretch along the road from Campo Grande to Coxim. This road passed partly through the upper watershed of the Taquari river (the Planalto, plateau). At some places local erosion features were observed. Most of the area is under soybean and during February soybean is at maturing stage, about 20cm above surface. Locally, especially at steeper terrain sections degraded forest is found. The nearly vertical sandstone escarpments near Coxim are hardly vegetated, other more gently sloping sandstone sections are covered with forest.
The vegetation is well adapted to slight changes in elevation along the river section surveyed. Vegetation (evergreen) within the active floodplain along the river on the levees is more than 10m high, locally trees are over 15m. Natural (deciduous) vegetation on the fan surface is open and generally lower, about 5 to 10m. A major portion of the fan surface is used for cattle ranging and is composed of extensive grass lands. Near the Caronal avulsion many lakes are found, on the shallow levees dead trees are present; in general the vegetation is 0,5m above the (water) surface composed of grass and reed species. Further downstream at the river banks the vegetation (water hyacinth and a type of reed/tall grass) is very dense making it difficult to determine the actual river bank. At locally higher portions (e.g. fossil levees which are found widespread due to the frequent river changes) trees are situated. Especially further downstream lakes are covered by water hyacinth.

3.5 Final DEM processing

Absolute accuracy assessment of the SRTM-DEM and DGPS measurements
After the DGPS measurements were post-processed the altitude was compared to the SRTM measurements. According to the SRTM product description the National Geospatial-Intelligence Agency (NGA) and contractors performed quality checks and additional finishing steps. One of these is that lakes of 600meter or more in length are flattened and set to a constant height and rivers that exceed 183 meters in width are delineated and monotonically stepped down in height. As all measurements are conducted along the Taquari and downstream reaches meeting above criteria it is possible that the altitude values are affected by this SRTM post-processing procedure. Table 3.1 shows the differences.

The difference given for the first measurement is most probably due to the spatial resolution of the SRTM data. The DGPS measurement was conducted next to the river, about 30m from the fan. The SRTM value is typically representing the altitude fan surface at that location. Largest deviations occur downstream with measurements conducted along the Paraguay Mirin. For these locations the SRTM has identical altitude values (89 m). The DGPS values are about 9 meter higher. This could be due to the SRTM finishing procedures as indicated above. All in all it can be stated that the absolute height accuracy is far better than the 16 meter (90 % confidence) as was specified for the mission.

Table 3.1 SRTM versus DGPS measurements

SRTM	DGPS	Difference
185	178.9971	6,0029
159	159.2523	-0,2523
139	142.411	-3,411
139	139.1613	-0,1613
135	138.3255	-3,3255
105	111.594	-6,594
89	98.2101	-9,2101
89	97.9044	-8,9044
97	99.0996	-2,0996

For further DEM optimization a new main drainage network digitized incorporating the findings from the field, especially with regard to the avulsions in the Caronal region. The drainage system is displayed as a vector overlay in Figure 3.1. Also the track record collected during the field survey was included (in Figure 3.1 displayed in yellow/white). Given time limitations a more detailed secondary drainage network could not be incorporated. The drainage was reclassified to reflect the main river systems in the Pantanal. Optimization parameters used are realistic incorporating the sounding observations that had been recorded during the field mission. The parameters used, for the respective runs, are given in Figure 3.2 (red/dark coloured boxes)

For run 4 the drainage optimization was slightly adapted, to simulate the present day active portion of the Caronal avulsion. An additional optimization step was implemented only at the active portion of the Caronal avulsion using the following optimization parameters for this small river reach: A, B, C: 180, 0, 2 respectively. The other optimization parameters are as in run 3.

Run	Second drainage			Taquari-Rio Negri			Paraguay			Paraguay Merin		
	A	B	C	A	B	C	A	B	C	A	B	C
1a	90	0	2	300	1	3	600	2	8	400	1	4
1b	180	1	2	360	2	4	450	5	2	360	3	3
1c												
2	180	1	2	360	2	4	450	5	2	360	3	3
3	180	1	2	360	2	4	450	5	2	360	3	3

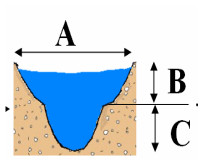


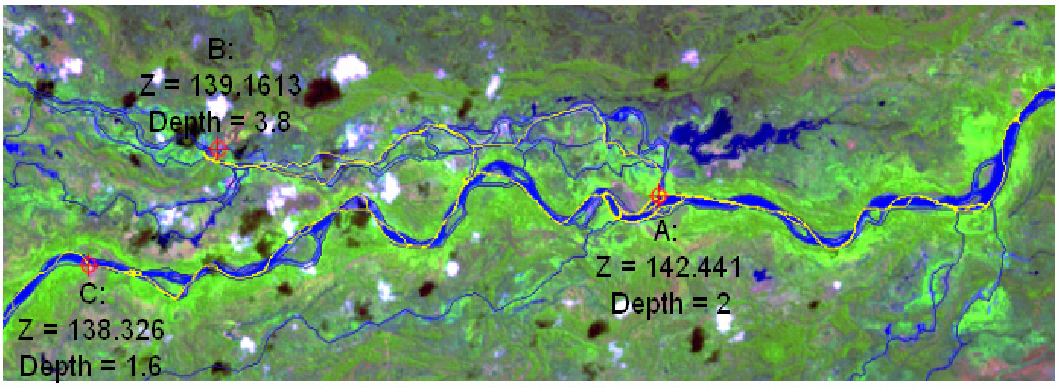
Figure 3.2 Drainage optimization parameters used

In order to obtain a hydrologically consistent DEM (water is draining to a specified outlet) first possible pits are filled in the DEM (no internal drainage). No control over the fill pit routine was applied resulting in the fact that e.g. a closed depression existing in the DEM would be removed and is "levelled" to the lowest outlet pixel altitude of this local depression. The GIS based flow direction routine used is the Deterministic–8 procedure followed by a flow accumulation routine. Setting a threshold on the number of contributing pixels to a certain outlet pixel allows for the extraction of the drainage network. This procedure was implemented in ILWIS using a newly developed software routine. In order to evaluate the relative accuracy of the processed and optimized DEM this extracted drainage network can be compared to the drainage from the satellite imagery available.

With regard to the DEM processing results of four runs conducted the following observations can be made with regard to the drainage network extracted:

- Model run 1 is using the (present) inactive Caronal avulsion as the main drainage channel.
- Model run 2 is using the Taquari as its main drainage channel configuration including the present day drainage configuration as found at the Zé da Costa avulsion.
- Model run 3 is using the (at present partially artificially blocked) minor avulsions at the left bank of the Taquari, just east of the Caronal avulsion, as its main drainage channel.
- Model run 4 extracts the drainage according to the present day situation as the drainage coincides with the active Caronal avulsion.

From these runs it is clear that the area around the Caronal avulsion is a very crucial region. Slight change in model parameters cause major changes in the main flow direction of the Taquari river at this location. Figure 3.3 is presenting the field observations collected at several positions at the avulsion as well as downstream. It is clear that especially the slope of the river bed (using the DGPS and sounding measurements) is greater within the Caronal avulsion compared to the Taquari. Figure 3.4 shows the sounding data collected. This information indicates that downstream of the Caronal avulsion the Taquari is very shallow and the river is substantially deeper within the active Caronal avulsion. During the survey it was clear that in this reach of the Taquari (just downstream the avulsion) overall active sedimentation was taking place. Furthermore in this reach a large number of (recent none vegetated) smaller sand bars and islands are located.



Gradient using Surface water profile			
Section	Length	Delta_Z	Slope
A-B	11748.68	3.2497	0.02766
A-C	14754.48	4.085	0.02768

Gradient using River bed profile			
Section	Length	Delta_Z	Slope
A-B	11748.68	5.0497	0.043
A-C	14754.48	3.685	0.025

Flow velocities in Caronal avulsion >5 km/hr

Figure 3.3 The Caronal avulsion.

As can be seen from Figure 3.4 there is a small gap in the sounding data recorded just downstream of the avulsion. This is due to the fact that the minimum water depth should be 60cm. This was not the case during the moment of the survey, shallow river sections are present here and we had to push the boat across these shallows in order to traverse the area. At the bottom of Figure 3.4 the present drainage layout 9s shown and the flow directions with respect to the avulsions occurring in the area. It is clear that a large amount of the discharge of the Taquari river is diverted here. During the moment of survey one of the avulsions, draining water to the south, was (partly) artificially closed.

To determine with more detail what the reasons are of the river's behaviour in this area a more detailed survey is needed. More detailed levelling data should be obtained. From the DEM model runs it is clear that minor adjustments can have major impacts on the fluvial system. Other, more regional phenomena should be included as well.

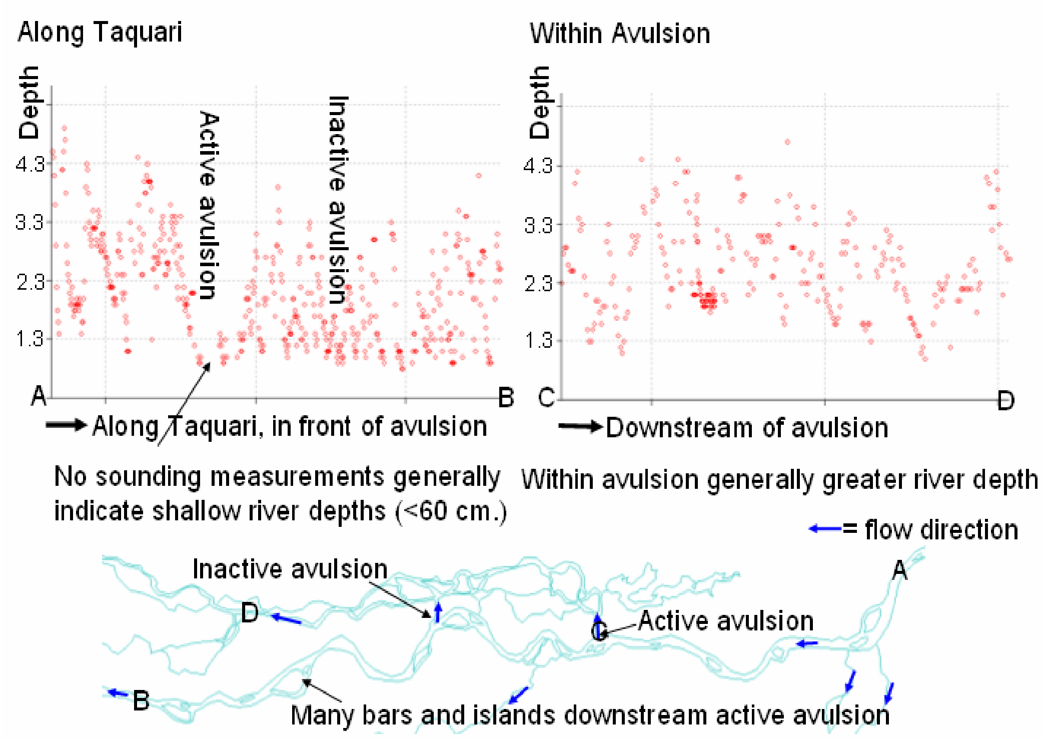


Figure 3.4 Sounding measurements Taquari and Caronal avulsion

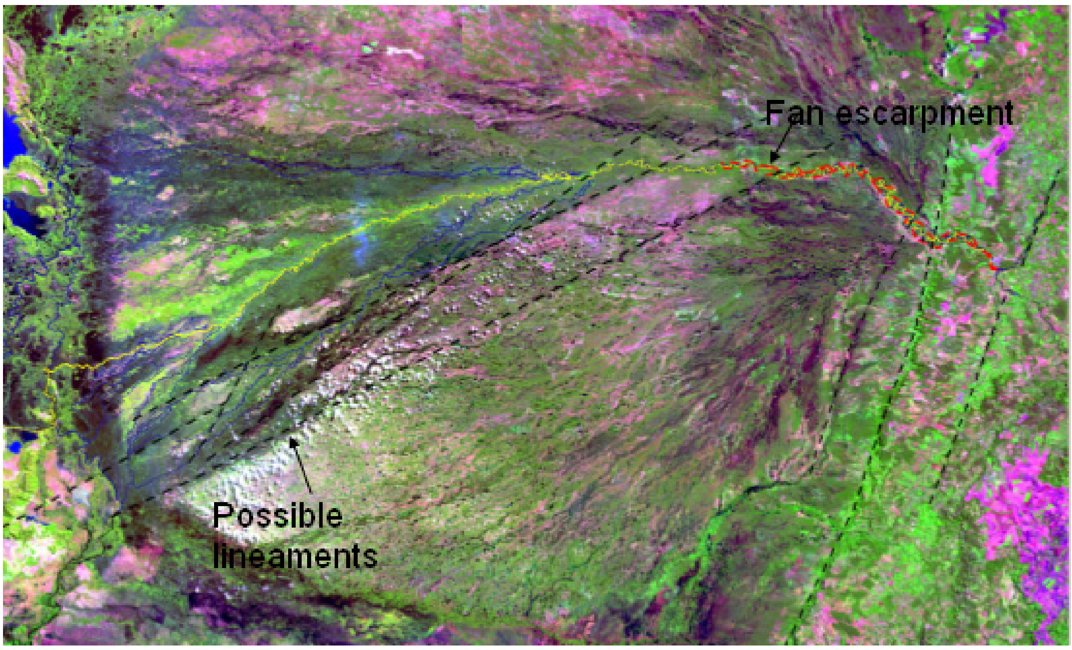


Figure 3.5 Lineaments identified crossing the Pantanal region (see also chapter 2)

The Pantanal, at its eastern perimeter, is bordered by the Plateau which was tectonically uplifted (with respect to the Pantanal) in the past. From literature references it is clear that also the Pantanal itself is affected by (neo) tectonic processes. Northeast-Southwest trending lineaments, that might indicate possible (neo) tectonic displacements, are interpreted from satellite images and are given in

Figure 3.5. These lineaments roughly mark the edge of the fan surface, south of the Taquari river. Where the lineaments cross the river, the river pattern is changing, east of the lineaments the river shows a high tendency to meandering, towards the west the river has a straighter pattern. It is remarkable that towards the west of the lineaments identified the avulsions start. As was shown by the DEM model results, small changes in river profile slope which may be due to possible neotectonic influences could be a reason for the avulsions in this area as well.

Extracted Drainage system
As stated above the extracted main river network is a good indicator of the relative accuracy. Run 4 is fairly well representing the actual conditions as found during the field survey and is given in figure 3.6 using the Landsat-TM image as background. The drainage extraction method used does not allow incorporation of avulsions, therefore the Taquari does not continue at the Caronal avulsion. This still means that when this DEM is incorporated in a hydro-dynamic model part of the flow would continue to flow through the Taquari.

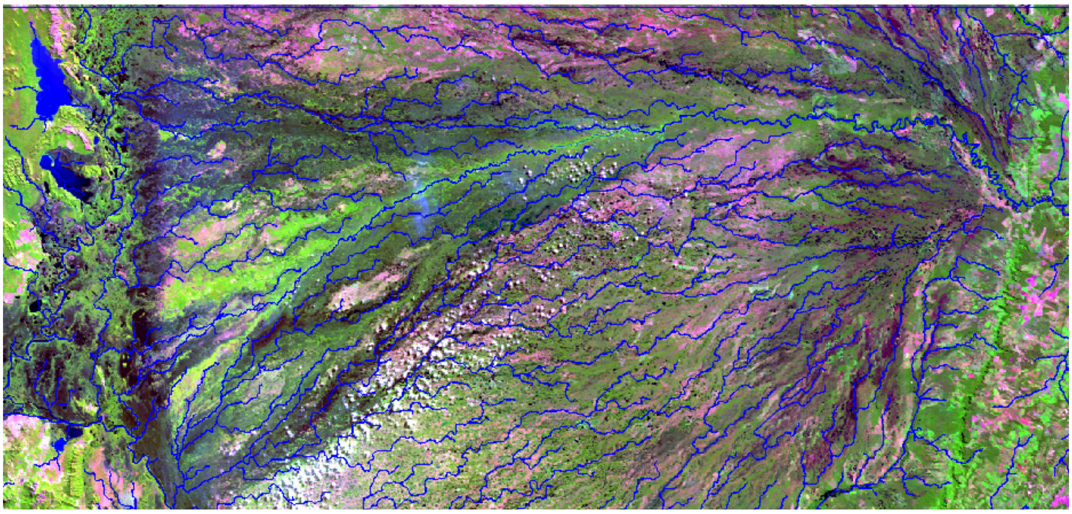


Figure 3.6 Extracted drainage

This is shown by the DEM of the Caronal region given in Figure 3.7. The arrows at locations B and C indicate the position of the Taquari river and other avulsions which is clearly visible by the deviating colour (e.g. cyan continuing in light green) showing the lower elevated portions for the river. The active Caronal avulsion is indicated by A. The black drainage lines indicate the extracted drainage, using a flow accumulation threshold of 4000 contributing pixels.

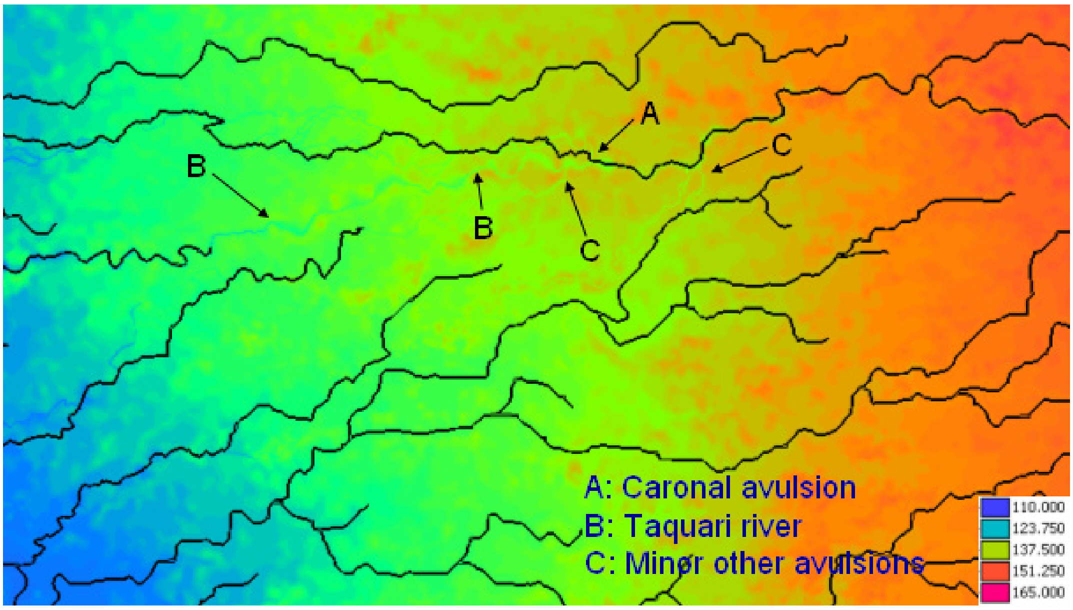


Figure 3.7 DEM of the Caronal region

As the minor secondary drainage is not used in the optimization process, there are deviations with regard to this drainage type when using smaller flow accumulation thresholds. It is thought that these differences will not seriously affect the use of the DEM for hydro-dynamic modelling.

Another way to evaluate the relative DEM processing results is to compare the difference map with the satellite images. The difference map was generated subtracting the processed DEM from the original DEM. Figure 3.8 is showing the difference map and the corresponding satellite image window.

The difference map displayed in grey scale is overlaid using with the satellite image and a linear profile tool is used to evaluate the absolute difference obtained along a section shown is the upper right sub window. The differences represent the height of the different vegetation types as observed in the field and the corresponding locations can be validated from the satellite images, e.g. the bright green vegetation along the river on the image represents evergreen trees mostly higher than 5 meters. The darker purple areas represent open areas which are scarcely vegetated and hardly any corrections have been applied in these areas.

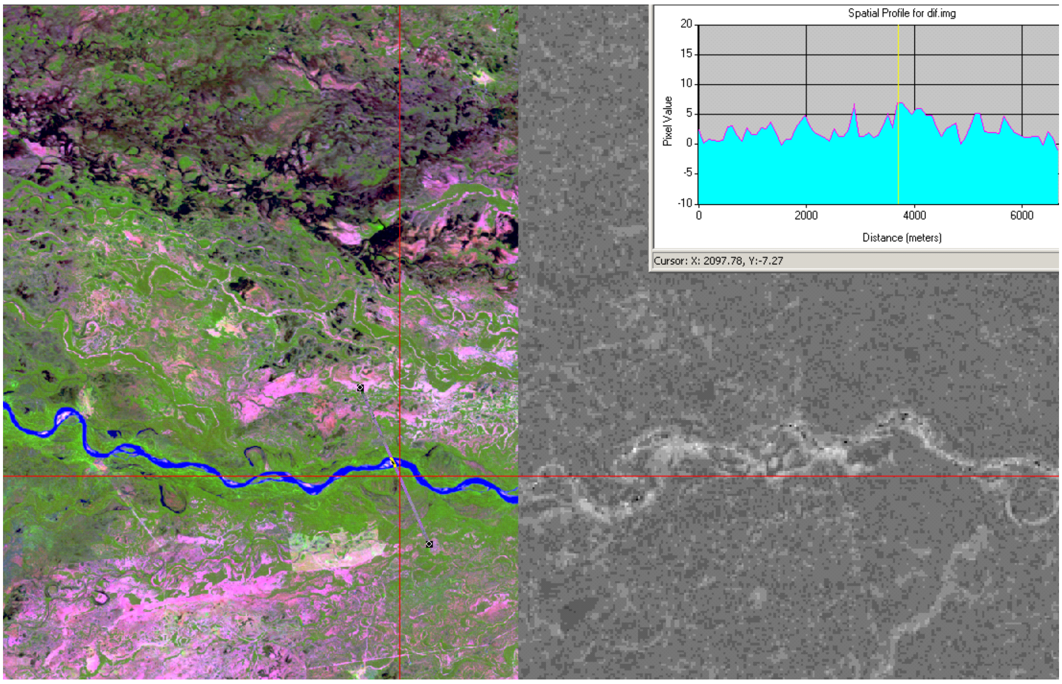


Figure 3.8 DEM difference map and satellite image window

The same procedure as indicated above can also be used to compare the satellite image with the processed DEM directly. Examples are given in figures 3.9 and 3.10. Figure 3.9 clearly shows the effects of the drainage optimization used. The riverbed is approximately 2,5 to 3m below the main terrain surface. The areas adjacent the Taquari river and Caronal avulsion are showing minor relief differences and even a shallow depression representing an infilled backswamp along the levee. Figure 3.10 is showing a 20km long section, from the uplands (south-east of Corumbá) into the Paraguay floodplain. The higher elevated Paraguay levees are the prominent elevated portions; the remaining areas are flat, showing local incisions when crossing minor drainage lines.

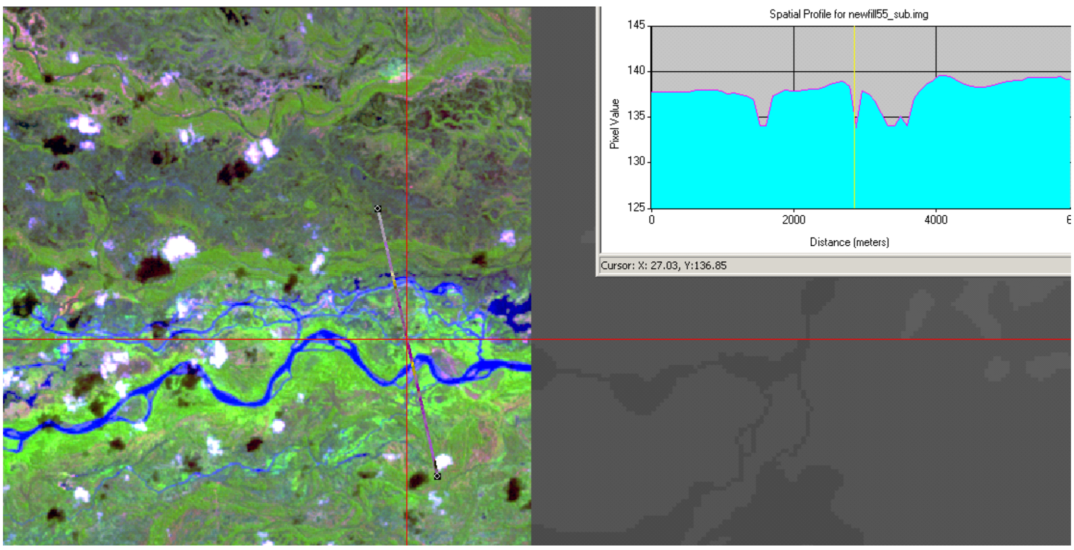


Figure 3.9 Processed DEM and satellite image window Caronal avulsion

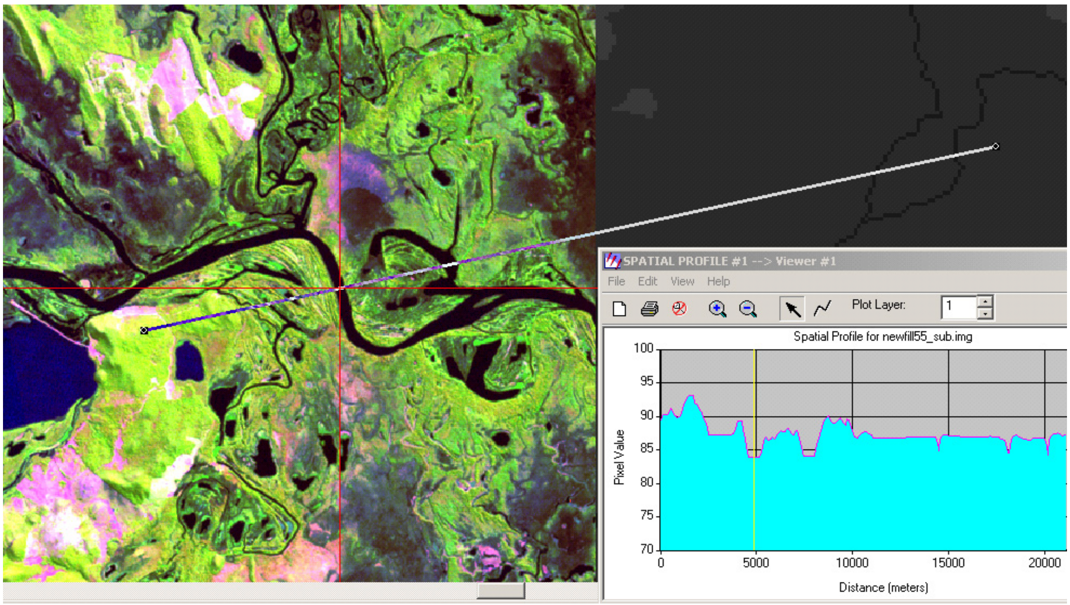


Figure 3.10 Processed DEM and satellite image window of the Paraguay floodplain

A final relative assessment conducted was reclassification of the difference map into elevation difference classes and draping these over the satellite image. These difference classes are representative of a number of prominent vegetation types occurring in the region like forest, bushes – shrubs – other herbaceous vegetation and reed – grass – water hyacinth. An example is provided in figure 3.11. As can be seen the levees along the Taquari as well as the fossil and secondary levees show another difference class expressing the relationship between slightly higher elevated terrain portions and their influence on the occurrence of evergreen tree species. In the backswamps hardly any height difference is computed, showing the minimal correction applied to reed and water hyacinth and no corrections at all in the case of open water bodies. The correction applied reflects the main morphology of the terrain and the relationship with the occurrence of vegetation. This fact could also be observed in the Paraguay floodplain.

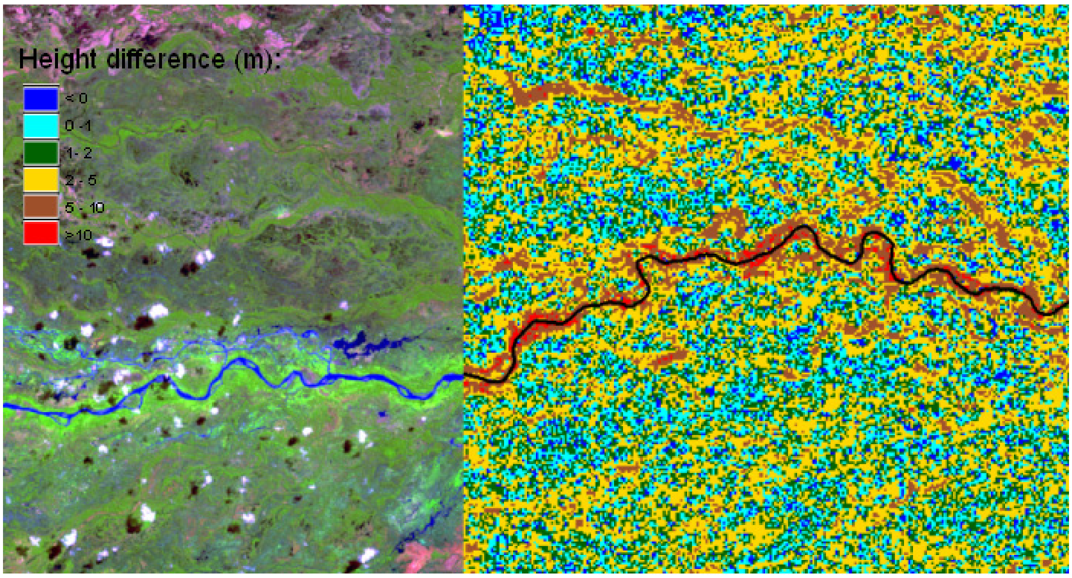


Figure 3.11 Spatial distribution of elevation differences computed

Figure 3.12 is showing the final DEM. The correction applied to incorporate the bathymetry is clearly visible. The DEM is visualized using a strong vertical exaggeration.

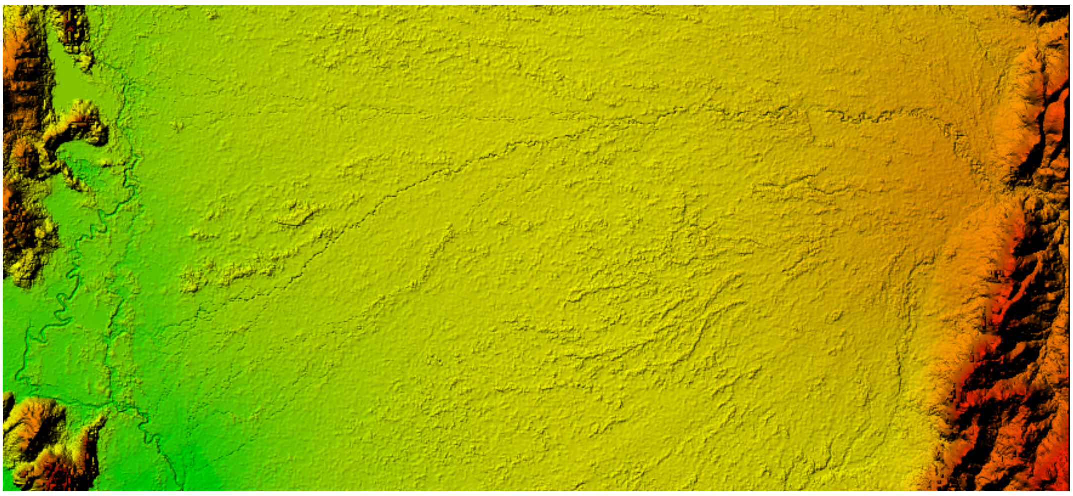


Figure 13.12 The Final DEM obtained

3.6 Conclusions

From the work presented in this chapter a number of conclusions may be drawn with regard to the first main problem stated in the introduction, namely: the development of a river flow and sedimentation model of the lower Taquari in the Pantanal. The model requires a good representation of the terrain. The effort presented here is reflecting this need. From the activities and analysis conducted additional conclusions can be made.

1. To cover the whole Pantanal region with laser scanning is not feasible. The only contribution that laser scanning could make is to further validate the DEM processing results conducted in this study. Laser scanning could be an option when a small area, like the Caronal avulsion, has to be studied in detail. This would also require adequate hydro-sedimentological data, which at the moment are not available, in order to successfully apply these dynamic models. Laser scanning is an operational technique in Brazil and three organizations are capable of doing the scanning and processing.
2. The field survey conducted provided a lot of additional information needed to perform the activities as given in this report. All data recorded could be successfully retrieved, (post) processed and integrated into a geographic information system to compare to available satellite images. As the area is very large and inaccessible the field observations made along the Taquari river are extrapolated to other regions in order to validate the DEM processing results. More fieldwork for a better assessment is needed.
3. The SRTM elevation model developed could also be used as an absolute model. The overall absolute vertical accuracy obtained is in the order of 5 to 10m, larger deviations occur in the Paraguay floodplain, most likely caused by finishing algorithms applied by the data provider. To overcome this problem the regression results presented could be adopted to get a more accurate altitude representation of this area. The absolute error is within the accuracy specifications given by the data provider
4. Several model runs are conducted. Run 4 represents the current diversion of discharge at the active Caronal avulsion and is regarded the best DEM.
5. The DEM optimization parameters used are realistic for the different drainage types in the Pantanal. Parameters B and C have been selected based on the sounding data collected and the width of the rivers (A) was measured directly from the satellite images and compared to the track records of the survey. Even after the fill pit routine (in the DEM hydro-processing stage) the river depth is realistic
6. The DEM processing could be successfully conducted using the process of hierarchic robust interpolation. The vegetation in the Pantanal region could be removed. The different runs conducted show deviating results with regard to the main drainage extracted, representing the importance of the Caronal avulsion area. Slight modifications have main implications over here. The parameters adopted in the filtering and interpolation routines are "over-removing" vegetation from the hills and the mountains bordering the Pantanal region. These areas should not be considered realistic.
7. The difference map produced (original SRTM_DEM – Processed_DEM) shows a good relationship with the different main vegetation type heights as found during the field survey. Also the morphology is fairly well represented.

As was described before, the Taquari River is traversing three distinct main landscape units and the avulsion areas are occurring in the gradual transition zones between these main landscape units: the Caronal avulsion is found in between the upper and the middle zone and the Zé da Costa marks the transition between the middle and lower zone. The differences in longitudinal profile in these zones should be measured more extensively before more conclusive statements can be made but given collected DGPS measurements small changes in slope do exist. A reason for this change in slope near the Caronal avulsion might be due to (neo)tectonic influences as the lineaments could be identified crossing the Pantanal from the North-east to the South-west. At the place where the lineaments are crossing the Taquari the river pattern starts changing as well.

4 Hydro-Meteorological data processing & development of the 2D Hydrodynamic model

Bob van Kappel[6], Marcel Ververs[7], Balbina Soriano[8], Sergio Galdino[9]

4.1 Introduction

A combined one-dimensional and two-dimensional SOBEK-model has been created as a part of the hydrological activities in this project. The SOBEK-model gives us an insight into the hydrological and hydraulic processes that play an important role in the Pantanal area.

The objectives of setting up the SOBEK-model are twofold:
- To better understand the hydrodynamic process in the Lower Taquari basin, by providing an answer to the following questions:
    - In what direction does the water flow?
    - Which areas are flooded and for how long are they flooded?
    - What are the water depths in the flooded areas?
- To obtain a tool to asses the hydrodynamic effects of possible measures (strategies) in the Lower Taquari basin

Data requirements
Data was collected to serve as input data for the SOBEK 1D2D model of the river Taquari in the Pantanal, Brazil. Data requirements for the set up of the SOBEK model are:
- Digital Elevation Model (DEM)
- Drainage network (including information about the dimensions of the network)
- Roughness estimates for the overland flows
- Inflows and outflows to and from the model; Water levels and discharges at the boundary locations (Coxim, Amolar and Porto Esperança)
- Precipitation and evaporation data of the Pantanal area

For the Paraguai river drainage data are available from the ANA database and for the Taquari river data from ANA, the PCBAP repast and field observations. In Figure 4.1 the main names and measure points in the study area are given.

The data from the PCBAP report were digitised first by a student. The data from the ANA database and from field measurements were digitally available, but had to be converted to a format used by SOBEK. The cross-sections were converted using an Excel spreadsheet.

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SOBEK uses a format, in which cross-sections are described by elevation values and corresponding distances from the left bank.

All data processing has been carried out in HYMOS. The sources of data were twofold: data downloaded from the ANA database and data supplied by Embrapa-Pantanal. Embrapa data were obtained through fieldwork.

The activities in this part of the project have been carried out by Bob van Kappel, Erik Mosselman and Marcel Ververs. Bob van Kappel was responsible for the hydro-meteorological data processing and for setting up the Hymos database. Marcel Ververs was responsible for the development of the 2-dimensional hydrodynamic model and for processing of the spatial data. Erik Mosselman was the project leader and he has reviewed the report. Balbina Soriano and Sergio Galdino made an important contribution to this research. They were responsible for collecting the meteorological and hydrological data respectively. Without this data the two dimensional hydrodynamic SOBEK model could not have been accomplished.

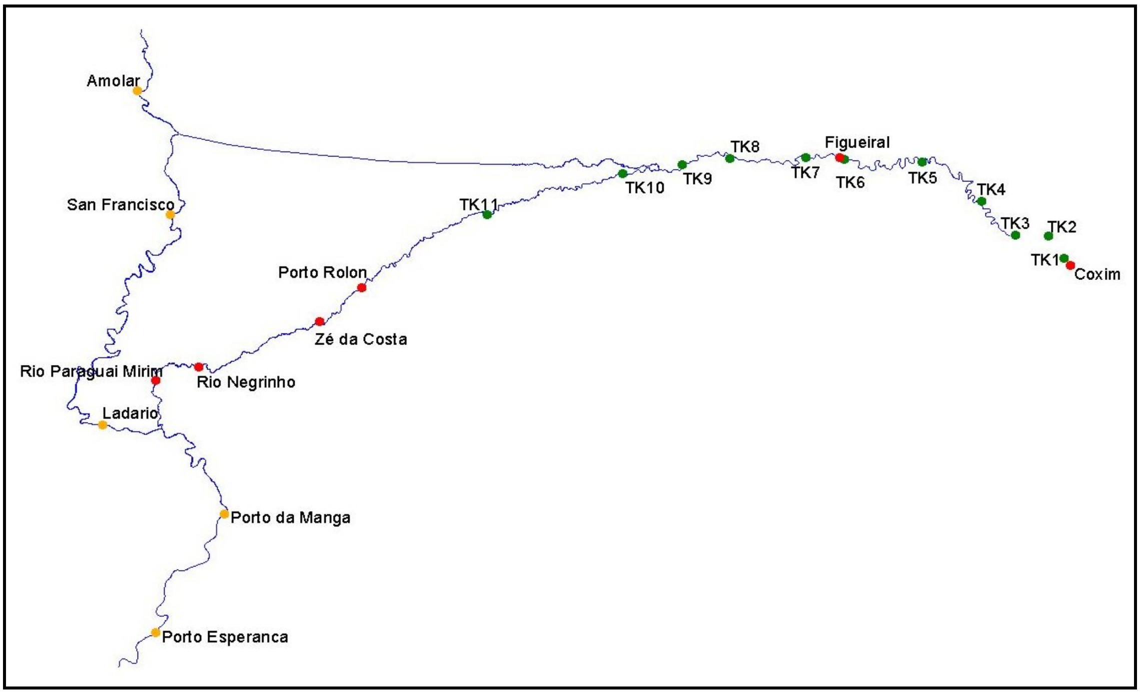

Figure 4.1 Important names used in this chapter and locations where cross-sections are available for the river Paraguai and Taquari.

Importing data to HYMOS

Data were provided from different sources in different formats. The main formats are Excel spreadsheets and ANA data in an Access database.

This chapter has been written to describe the procedure that has been followed to import the ANA and other data to the HYMOS database. In the basic report the description has been made to a very high level of detail, such that it resembles a manual. This was deemed necessary, in addition to the existing HYMOS manual, and also on the request of Embrapa.

It is very important to be critical about all data that are imported into HYMOS, irrespective of the source of the data. There are many options in HYMOS to present and screen the data for possible errors. Early detection of errors will save a lot of time later in the modelling process.

The Agência Nacional de Águas (ANA) through its website supplies data in its own database format. This format does not allow easy conversion into a format that can be used in other programmes. ANA does supply a programme to work with the data: Hidro. This program however does not provide an export facility to create easily readable files for further data processing in other systems. A conversion tool has therefore been made to read an ANA database and export selected time series data in an easily readable format (Figure 4.2). The conversion tool can also create an import file for HYMOS

The conversion tool has been used to convert all data that had been downloaded from the ANA website. Most of the series that were converted had one or more periods of missing data, periods that are not identified as such in the database.

The import procedure that was followed in HYMOS to import the data depends on whether Equidistant data or Non-Equidistant were created by the conversion tool. Before importing it is necessary to verify that the time series that will be imported exist in the HYMOS database. Select the Location, Parameter and correct Time Base settings and verify that indeed a series exists. If this is not the case, create the series first. Equidistant data import is done through the import/Export function of HYMOS.

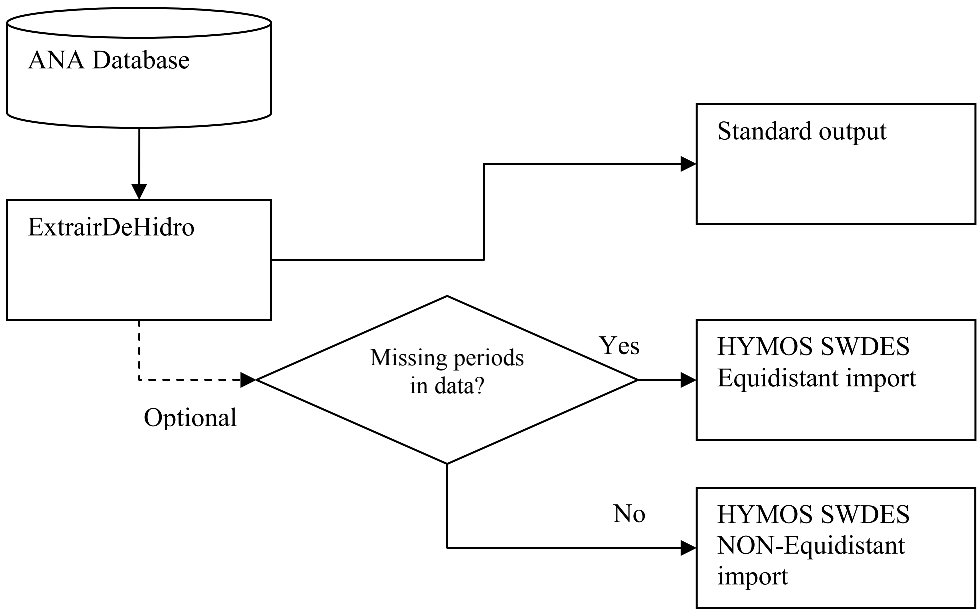

Figure 4.2 Conversion of ANA data into HYMOS

4.2 Hydrological data processing

The hydrological year that is used spans from 01 October - 30 September.

Rio Taquari
Coxim (ANA ID 66870000) is an upstream boundary location for the SOBEK model. The data required are discharge data for the hydrological year 1999 - 2000, at a daily interval. The following data were made available: (in parenthesis the HYMOS parameter)

- Water Levels (HH) : 01 Jan 1966 - 31 Dec 2002
- Discharge (QH) : 01 Jan 1966 - 31 Dec 1995
- Discharge measurements: 36 events, starting 28 Jan 1966 - 05 Sep 2003

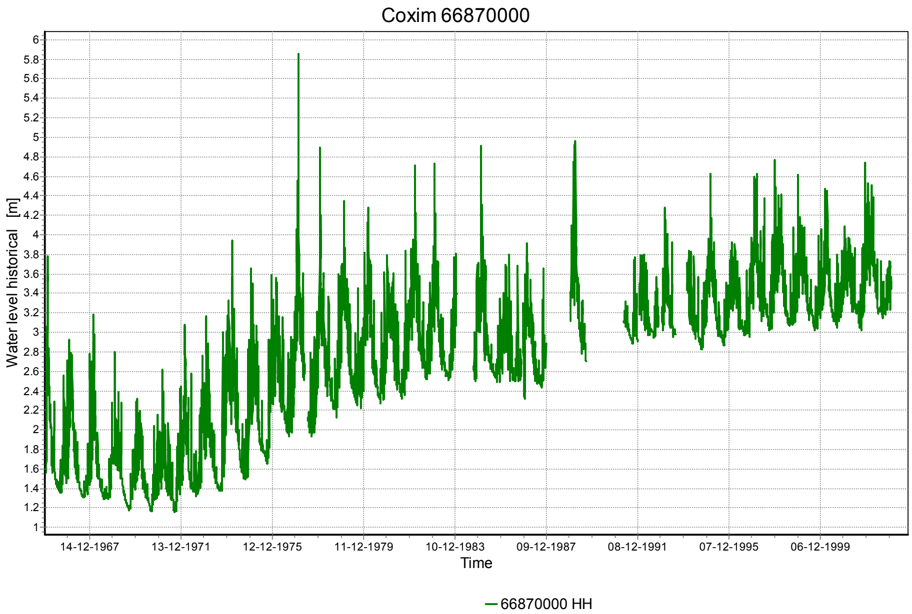

Figure 4.3 Water Levels at Coxim

Figure 4.3 shows the original water level series as they have been obtained from ANA. A distinct trend showing a continuous rise of the lower water levels is visible.

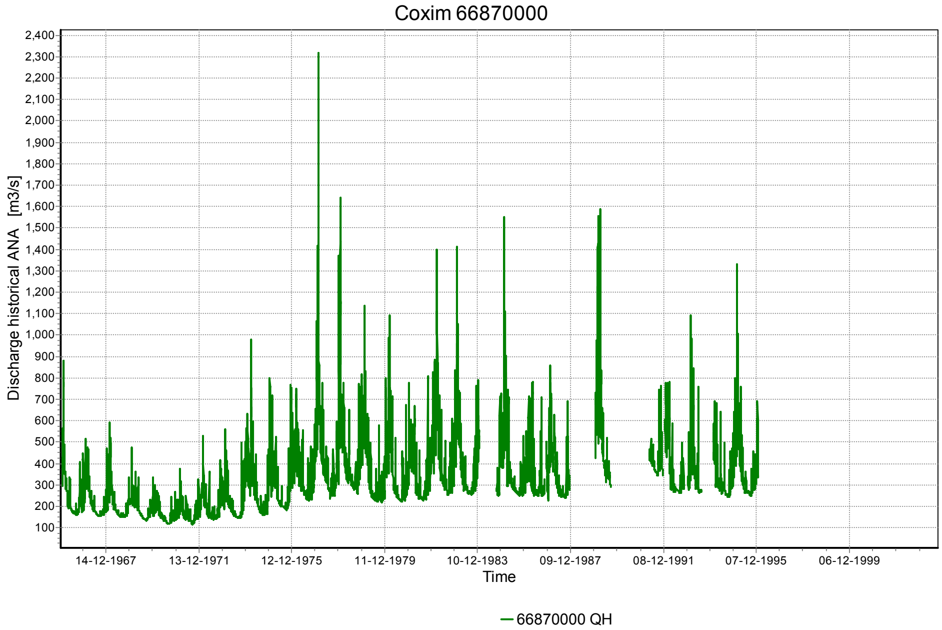

Figure 4.4 Discharge at Coxim

Figure 4.4 shows the discharge data as it has been obtained from ANA. The lower discharges show a similar, but somewhat less distinct rising trend of the minimum values. In fact, no real trend can be seen, but only a slight rising is visible in the years 1976 - 1979. Figure 4.4 has been made using the exact same time scale as Figure 4.3. Discharges for the required period of 1999 - 2000 are not available.

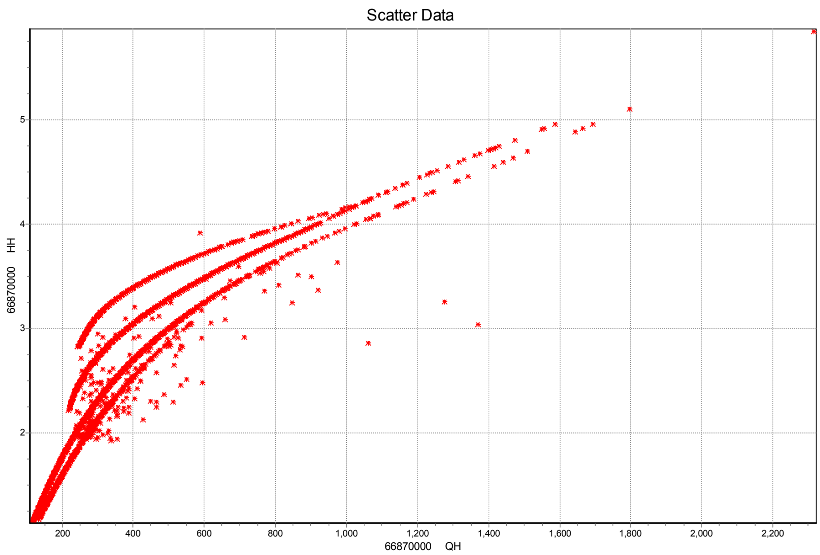

Figure 4.5 Scatter plot of Water levels (horizontal axis) against Discharges (vertical axis), 1966-1995

A rating curve for the station is not available, but discharge measurements are. Before a rating is made, a simple validation of the rating curves used for the discharges is made, by plotting Water Levels against the Discharges in a scatter plot. The scatter plot will reveal the relation that has been used to calculate Q(t) from H(t), if any.

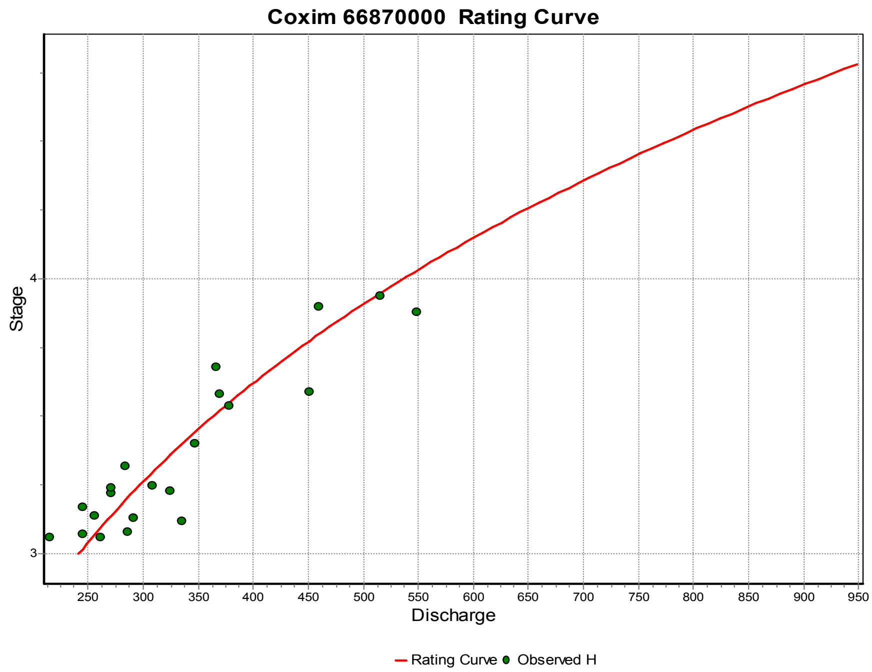

Figure 4.6 Coxim rating curve

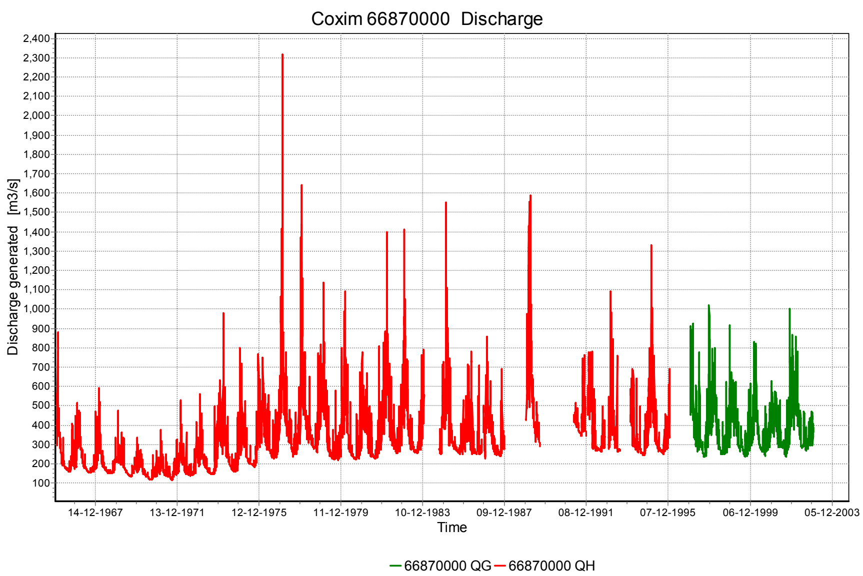

Figure 4.7. Generated and ANA discharges at Coxim; newly calculated discharges are at the utmost right side (1997–2003, green).

Figure 4.5 shows that at least 4 distinct ratings curves have been used for the calculated discharges. Further detailed analysis has also shown that the rating curves in time shift from bottom to top (or from right to left) in the plot, indicating lower discharges at the same water level. For the period January 1966 to December 1995 the shift indicates a raised bed level of approximately 1 meter.

The final rating curve is presented in Figure 4.6. Note the large amount of extrapolation that was needed to enable the rating curve to be used for the full range of measured water levels (3 - 4.8 m). Under optimal circumstances the extrapolation would have to be supported by at least a cross-section, the hydraulic roughness in the cross-section and the energy slope of the water level at the cross-section. In this case the data required were not available.
Discharges were calculated using the established rating curve. The discharge that is entered into the model is shown in Figure 4.7.

Rio Paraguai
Amolar (ANA ID 66800000) is an upstream boundary location for the SOBEK model. The data required are discharge data for the hydrological year 1999 - 2000, at a daily interval. The following data were made available: (in parenthesis the HYMOS parameter)

- Water Levels (HH) : 16 Nov 1967 - 30 Nov 2003
- Discharge (QH) : 16 Nov 1967 - 30 Nov 2003
- Discharge measurements: 66 events, starting 29 Jul 1969 - 05 Dec 2003

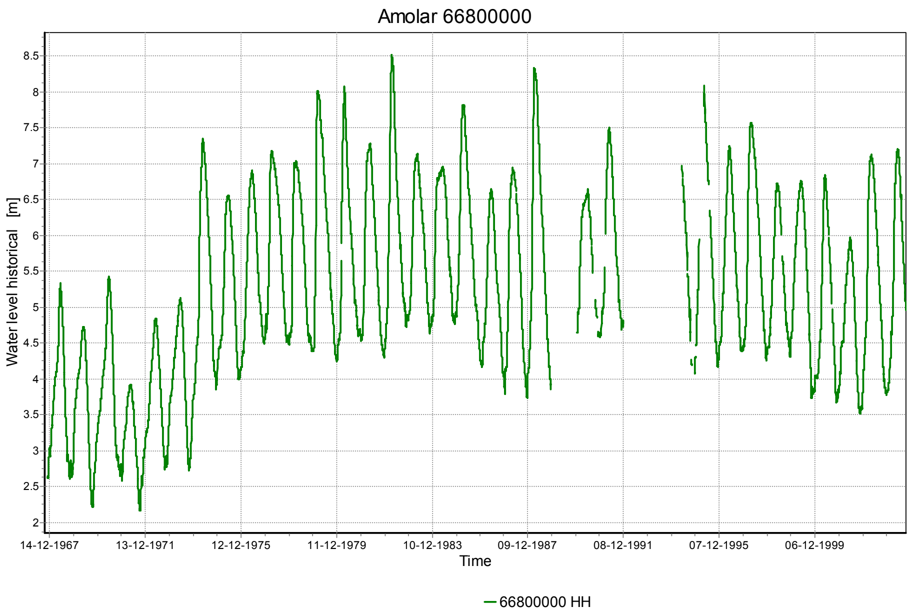

Figure 4.8 Water levels at Amolar

Figure 4.8 shows the imported water levels at Amolar. Similar to Coxim, here also a rise in minimum water levels is seen. The rise at Amolar however is seen some years before that of Coxim, notably during the years 1972 - 1975. Some periods of data are missing.

Figure 4.9 shows the imported discharge at Amolar. Comparing the water level series and the discharge series it is noted how very similar these appear to be.

Figure 4.10 shows the rating curve derived from the available discharge measurements. Some dispersion of the measurements around the regression line is seen, but the linearity of the rating curve is surprising. The derived rating curve is a power type rating curve, with a power equal to 1.3, i.e. close to linear. The derived rating curve compares very closely to the applied rating curve, indicating no apparent error in the discharges.

São Francisco (66810000) is located approximately 60km downstream from Amolar. This location has data for more or less the same period as Amolar and may serve to verify the discharges at Amolar.

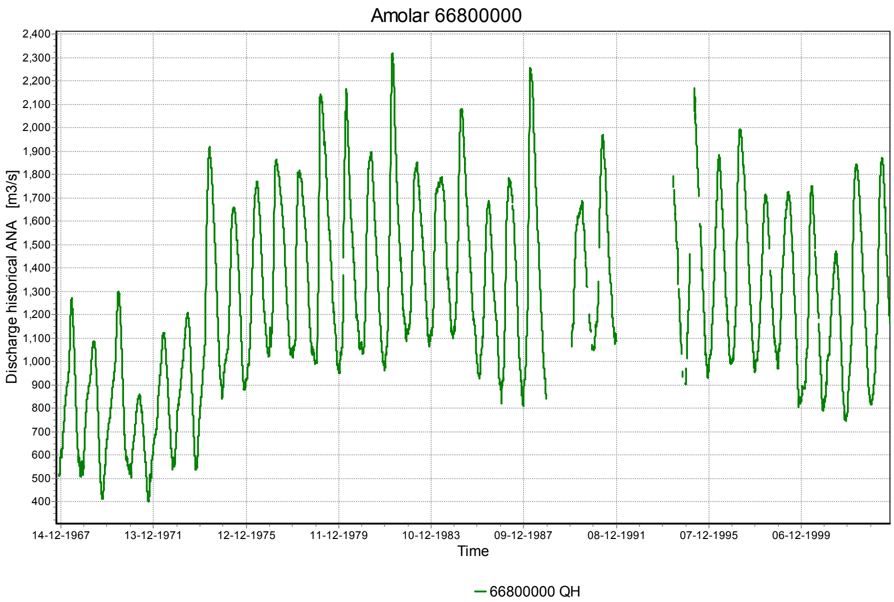

Figure 4.9 Discharge at Amolar

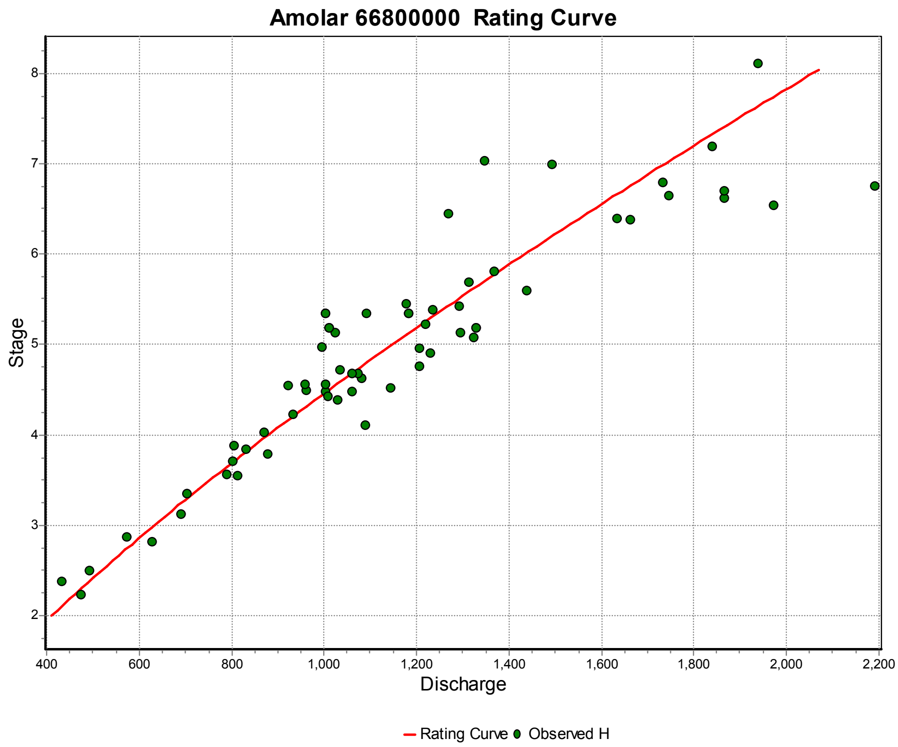

Figure 4.10 Calculated rating curve with discharge measurements used to derive the curve

A first comparison of imported ANA discharges for São Francisco with those of Amolar shows a considerable difference in the discharges at the two locations. Figure 4.11 shows the discharges at Amolar in green and the discharges at São Francisco in Red. While the lower discharges are very much similar, the higher discharges at São Francisco are considerably higher than those of Amolar. At peaks the differences can amount to a maximum of 2.800m^3/s (2.200m^3/s at Amolar and 5.000m^3/s at São Francisco in April 1995). Without a major contribution into the river Paraguai between Amolar and São Francisco this difference in discharge is hard to explain. Further research into these differences is obviously required.

For the time being the discharge at Amolar is used for the SOBEK model. For the hydrological year 1999 - 2000 two minor periods of missing data needed to be filled. This has been done with simple linear interpolation (Figure 4.12).

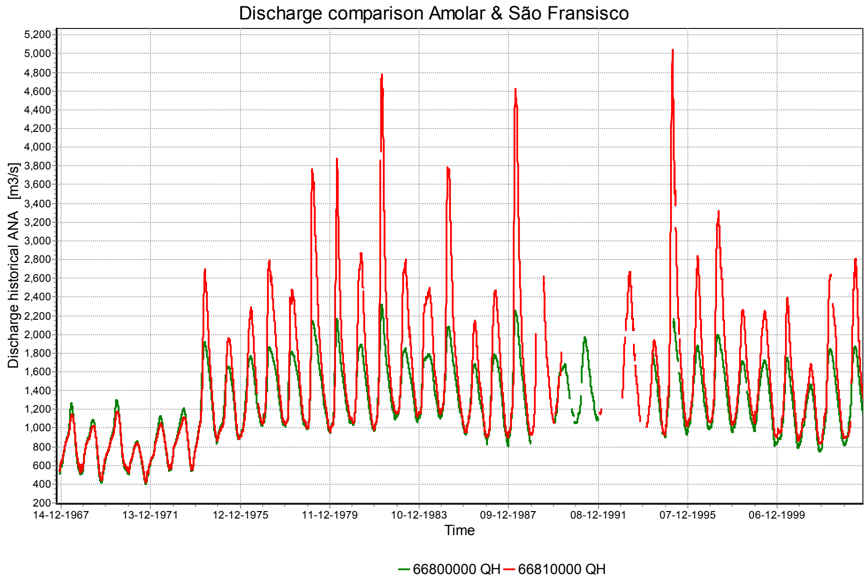

Figure 4.11 Comparison of discharge at Amolar & São Francisco

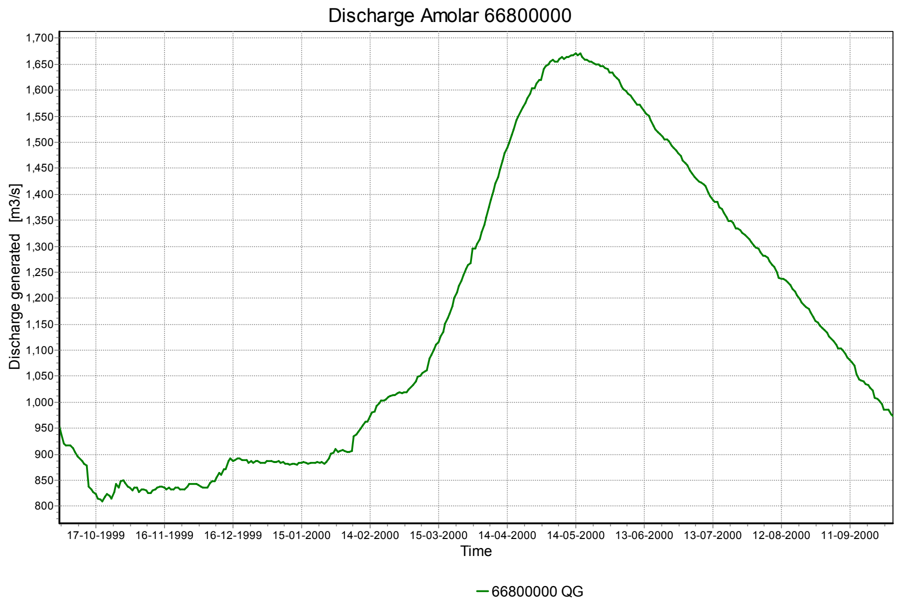

Figure 4.12 Discharge at Amolar for hydrological year 1999 - 2000

Porto Esperança (ANA ID 6696008) is the only downstream boundary location for the SOBEK model. The data required are water levels for the hydrological year 1999 - 2000, at a daily interval.

The following data were made available: (in parenthesis the HYMOS parameter)

- Water Levels (HH) : 19 Dec 1963 - 31 Oct 2003
- Discharge (QH) : 19 Dec 1963 - 31 Dec 1981

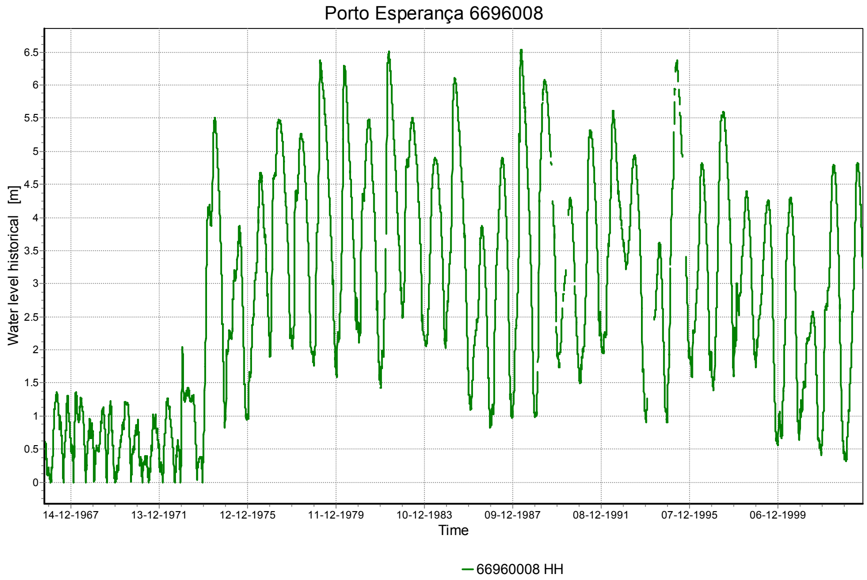

Figure 4.13 Water levels at Porto Esperança

Figure 4.13 shows the water levels at Porto Esperança. A clear error in the period 1963 - Dec 1973, where water levels below the scale zero have been mirrored to positive values is visible. No further validation has been made of the Porto Esperança water levels. This leads to a corrected series used in the model as given in Figure 4.14.

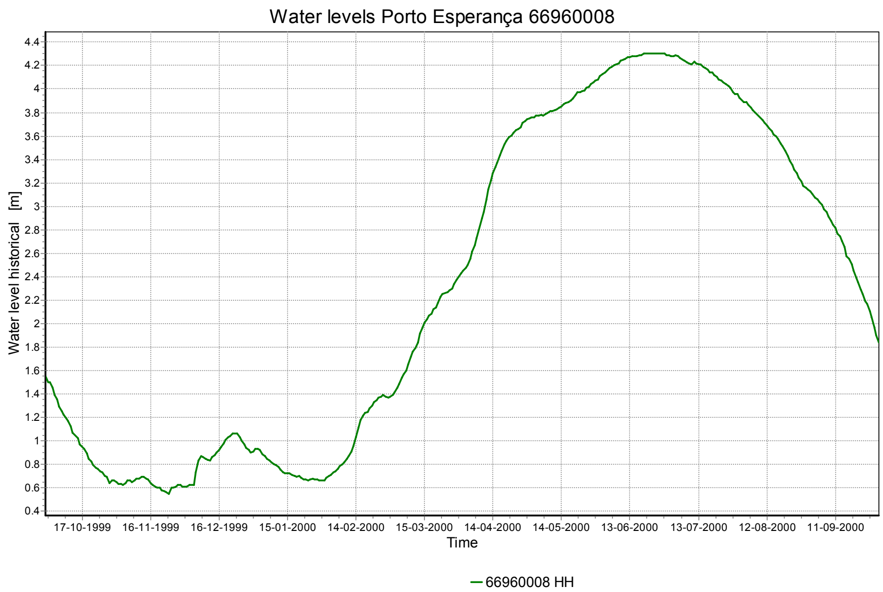

Figure 4.14 Water levels at Porto Esperança

4.3 Generation of Scenario Time Series

Scenario time series are required as alternative input series for the SOBEK model. The model has been calibrated on the actual series of the hydrological year 1999 - 2000. For the alternative model runs, the following alternative series are required:

- 90% dry year
- average year
- 90% wet year

The input time series for SOBEK for which alternative series are created are:

- Discharge at Coxim
- Discharge at Amolar
- Water Levels at Porto Esperança

Using the Frequency - Duration curves function in HYMOS, the required series can be generated. Setting the Time base to the Hydrological year ensures that the series that are created comply with the hydrological year.

The Frequency Curves are created for a 90% Wet, 90% Dry and an average year. For a Dry or Wet year, *for each day of the year* the function will return the value that is exceeded by 90% of all available values *for that day of the year*. The year that is obtained is therefore not a real year, but a sequence of dry, average or wet days.

In Figure 4.15 the frequency curves for discharge at Coxim are shown. The frequency curves are derived from combined historical discharge and the discharges generated using the new rating curve. The period of data that was used is from 1 October 1966 - 1 January 2003. Besides the Wet, Dry and Average years, also the hydrograph of the 1999 - 2000 hydrological year is shown. The HYMOS series that was used is QS.

Note that the hydrographs of the frequency curves is much smoother than the hydrograph of 1999 - 2000. This is a result of the chosen procedure, in which the Dry, Wet and Average days in the year are combined into to a single year.

Figure 4.15 shows that a number of peak flows was higher than the 90% Wet flow for the period. On the whole 1999 - 2000 appears to be fairly wet, especially the second half of the year.

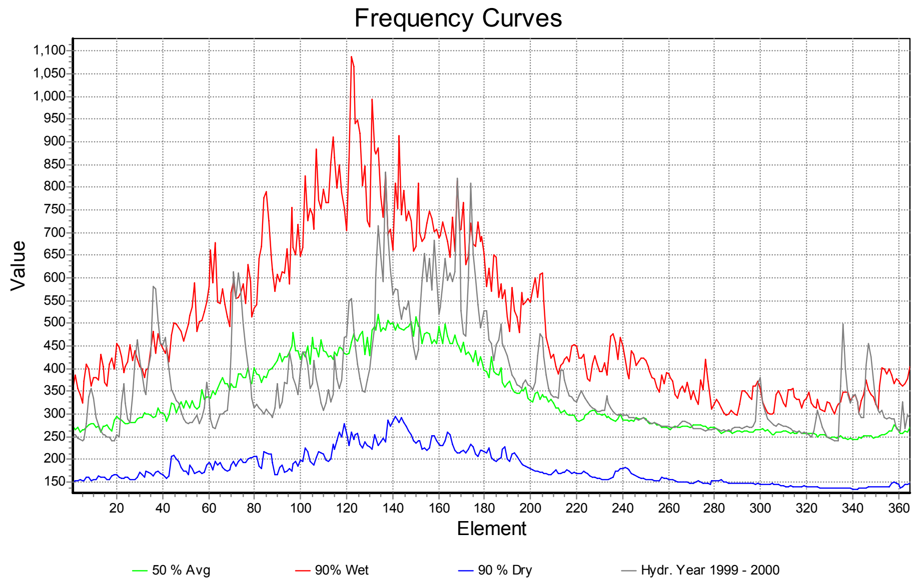

Figure 4.15 Hydrological year 1999-2000 and frequency curves for discharge at Coxim

In Figure 4.16 the frequency curves for discharge at Amolar are shown. The frequency curves are derived from the discharges generated by using the new rating curve. The period of data that was used is from 01 January 1969 - 01 October 2002. Besides the Wet, Dry and Average years, also the hydrograph of the 1999 - 2000 hydrological year is shown. The HYMOS series that was used is QG.

An interesting observation from the frequency curves is that the time of the peak discharge for drier years is later in the year than for wetter years. The hydrological year 1999 - 2000 appears to be a below average year.

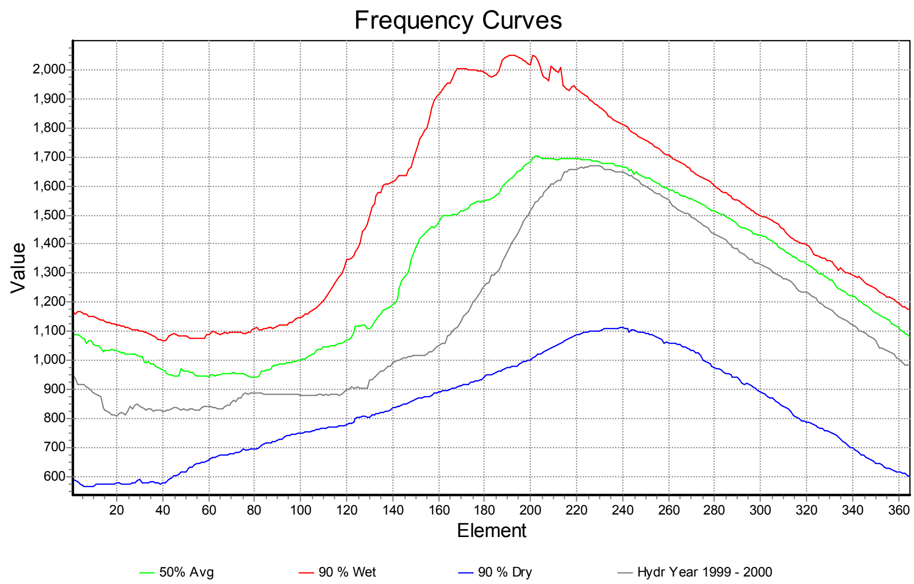

Figure 4.16. Frequency Curves for Discharge at Amolar

In Figure 4.17 the frequency curves for water levels at Porto Esperança are shown. The frequency curves are derived from the original water levels. The period of data that was used is from 01 January 1974 - 01 November 2003. Note that the erroneous water levels of the period up to 1974 were not used. Besides the Wet, Dry and Average years, also the hydrograph of the 1999 - 2000 hydrological year is shown. The HYMOS series that was used is HH.

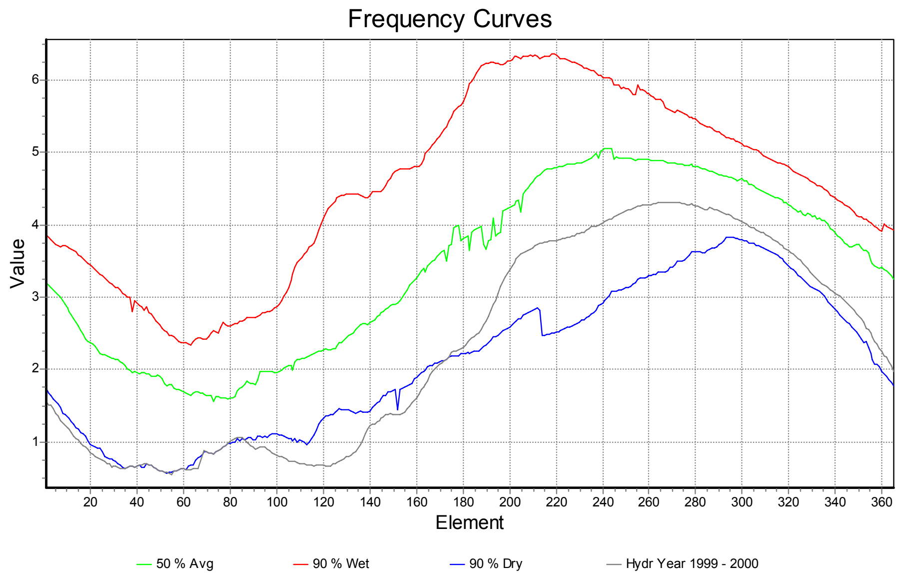

Figure 4.17 Frequency Curves for Water Levels at Porto Esperança

The 1999 - 2000 hydrological year clearly shows the influence of the relatively wet conditions in the Taquari basin in the later half of the year. The water levels at Porto Esperança in the later half of the year exceed the average conditions, whereas at Amolar the conditions remain under the average conditions.

The sudden drop in dry conditions seen around day 200 - day 220, or more or less in April, seems somewhat strange. Further research into the time series may be required to explain this, if it cannot be explained simply by an error in the time series. No further analysis has been made yet. The same is true for the downward spike around day 150.

4.4 Meteorological data processing

Meteorological data in the SOBEK model are applied using a single time series that represents the aerial average of the parameter concerned. For the model that has been set up only precipitation and evaporation has been used.

Precipitation data

Precipitation data are available for a number of locations within and in close proximity of the Pantanal. Most series, however, have significant periods of missing data, illustrated in Figure 4.18.

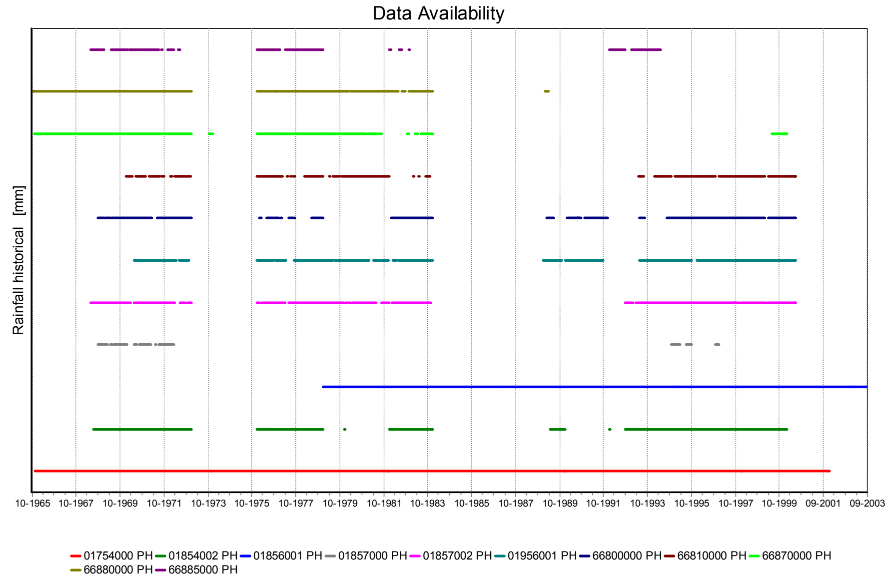

Figure 4.18 Data availability of 11 Precipitation data series

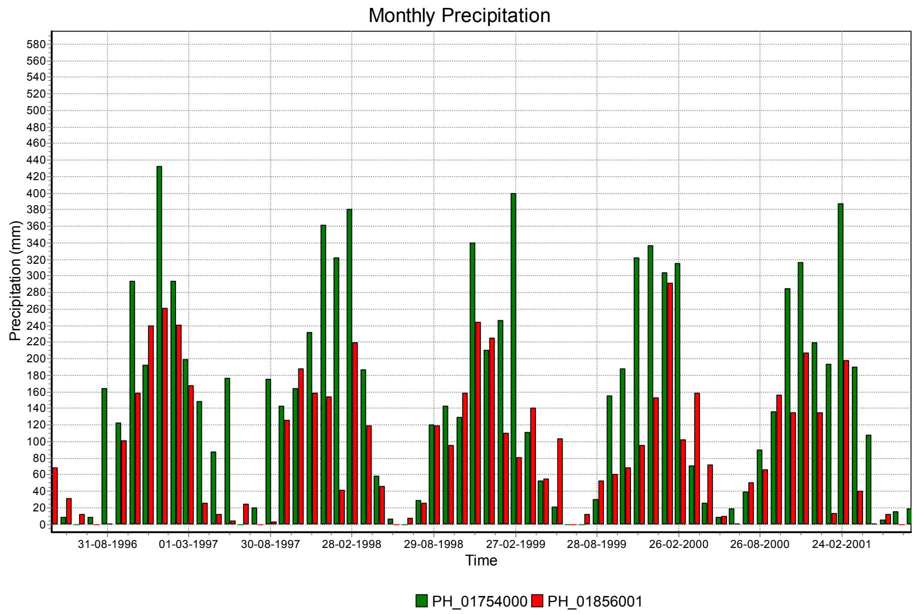

Figure 4.19 Monthly precipitation at Itiquira (Green) and Nhumirim (Red)

Only two stations show complete data series, for the period covering beginning 1979 to end 2001. The two stations are Itiquira (017540000) in red and Nhumirim (01856001) in blue. Itiquira, situated on the Planalto does show considerably more precipitation than Nhumirim, as illustrated in Figure 4.19.

For the SOBEK model a straightforward linear average has been made of the two series. It is assumed that for the moment this provides a sufficiently good estimate of the areal rainfall of the Pantanal. For the hydrological year 1999 - 2000 this results in a series being used as presented in Figure 4.20.

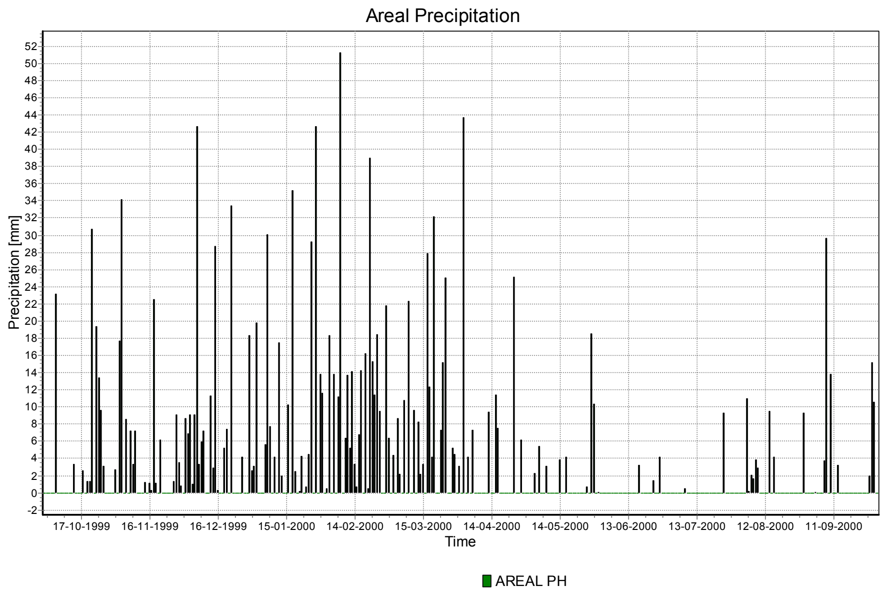

Figure 4.20. Aerial Precipitation

Evaporation data

Evaporation data are available only at station Nhumirim. The complete series is shown in Figure 4.21.

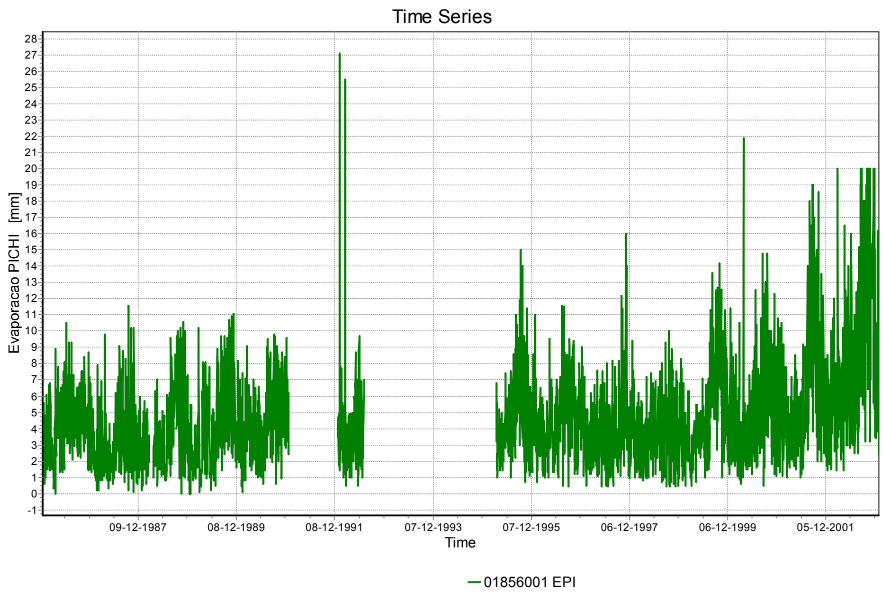

Figure 4.21 Daily evaporation at Nhumirim, Jan 1986 - Dec 2002

Figure 4.21 shows a probably serious problem starting around July 1999, when daily evaporation values seem to start rising, and continue to rise. This is clearly illustrated, when the moving average of the daily series for a period of 60 days is plotted in the same graph, see Figure 4.22

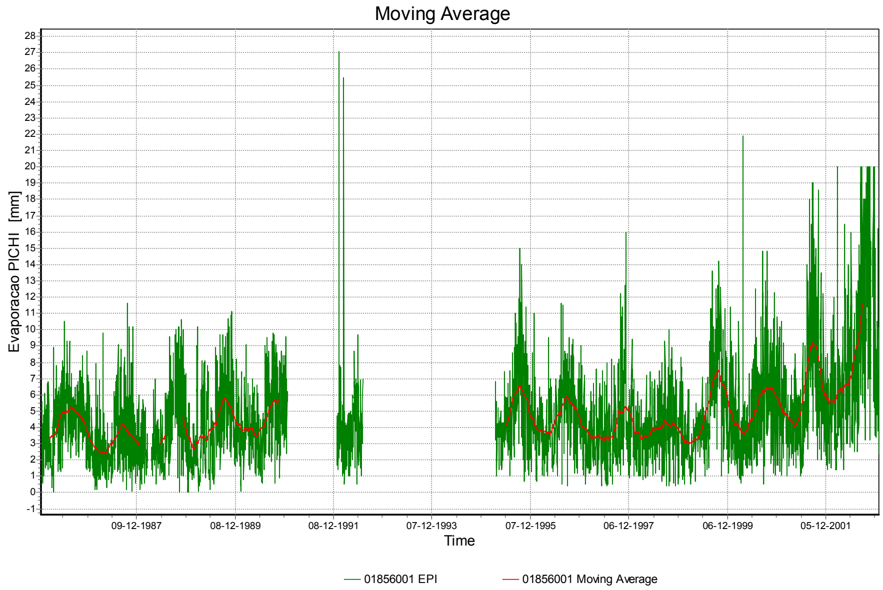

Figure 4.22 Daily evaporation including 60 day moving average

The problem may be have a natural cause, but can also be due to a change in the calculation procedure. However, this could not be confirmed and needs to be verified. Meanwhile the evaporation data used in the model are the 60 day moving average for the hydrological year 1996 - 1997, assuming that this daily evaporation value is representative for the area as a whole (Figure 4.23).

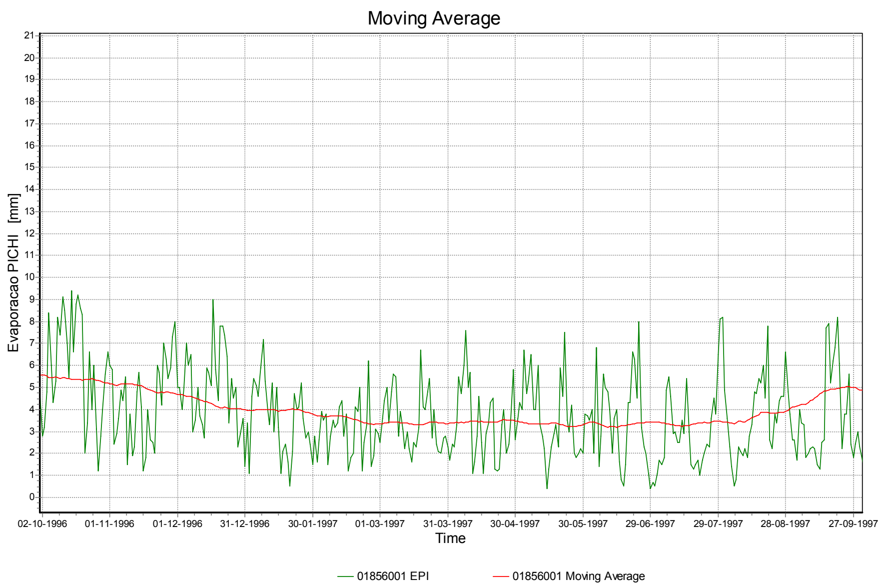

Figure 4.23 Evaporation for Oct 1996 - Oct 1997 including evaporation profile (60 day moving average)

4.5 Generation of Scenario Time Series

Scenario time series are required as alternative input series for the SOBEK model. The meteorological input data for the SOBEK model are catchment average rainfall and evaporation. Precipitation data are obtained as an average of two time series. For this average series the frequency curves can be established. For the evaporation series no scenario time series are required because the evaporation data used in the SOBEK model are regarded as potential evaporation.

Precipitation

If the frequency curves for precipitation data would be established in the same manner as for the water levels and discharges, most or even all the 90% dry values would be equal to zero and the 90% wet values would show precipitation at most or all days. This is clearly not correct. The reason for this is that precipitation data are not continuous. In order to obtain a reasonable estimate the following procedure has been used:

1 Establish the monthly sums for the precipitation series.
2 Obtain the frequency curves for the monthly sums.
3 Upscale or downscale the values of the 1999 - 2000 hydrological year such that the monthly sum represents the dry, average of wet frequency curve.

Note that this is a rough procedure. The number of rainy days in each month remains the same, which is obviously a simplification of the actual situation. In Figure 4.24 the frequency curves for monthly precipitation of the aerial average are shown. The period of data used is from 01 January 1979 - 01 January 2002. The HYMOS series that was used is Aerial PH.

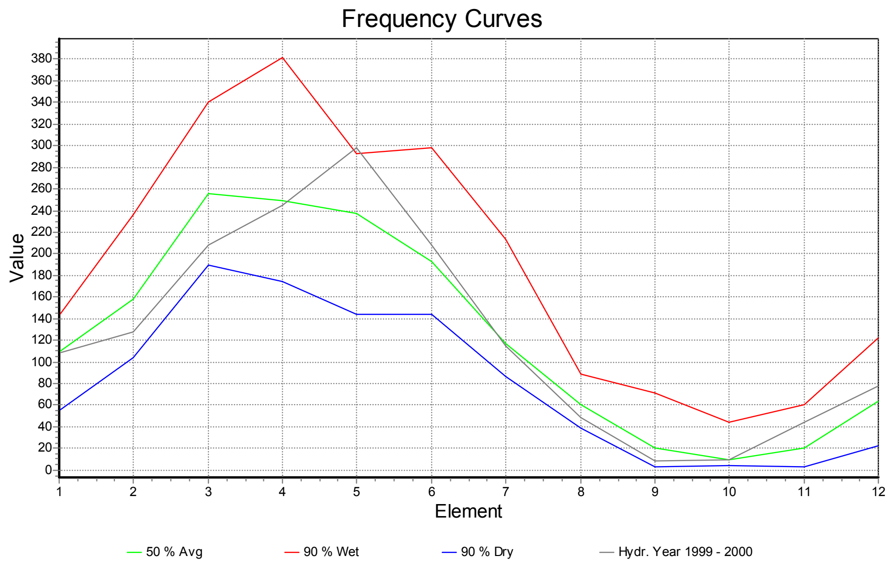

Figure 4.24 Frequency curves of monthly precipitation

Based on the above frequency curves, the daily values for an average, dry and wet year were established. The upscaling or downscaling of the data has been carried out in Excel.

4.6 Overview of data used in SOBEK model

This section gives an overview of the data used in the latest version of the SOBEK model and the data that have been prepared for use in the three scenarios and for calibrating the model. The river channels need input, which is specific for that channel. The first two paragraphs describe the input data used for the river Paraguai and the river Taquari. The last paragraph gives information on the parameters, which are applicable for the whole model.

River Paraguai

The following data were used for the river Paraguai:

- For the river Paraguai profiles from the ANA-database from the year 1999 were used
- For all cross-section locations a hydraulic Nikuradse roughness of 0.003 m is defined for the river bottom and embankments
- Discharge data at Amolar extracted from the Hymos database for the period 01-10-1999 to 30-09-2000 were used
- Water level data at Porto Esperança from the Hymos database for the period 01-10-1999 to 30-09-2000 were used
- A shapefile based on a recent satellite image with the exact location of the river Paraguai following the drainage pattern from the DEM
- For the 'wet', 'dry' and 'average' scenarios, discharge data at Amolar and water level data at Porto Esperança were used.

River Taquari

The following data were used for the river Taquari:

- For the river Taquari profiles from the ANA-database (1999), from a PCBAP report (September 1995) and from fieldwork done by Carlos Padovani were used. Locations of these profiles were given (in UTM coordinates or geographical coordinates (latitude/longitude))
- For all cross-section locations a hydraulic Nikuradse roughness of 0.003 m is defined for the river bottom and embankments
- Discharge data at Coxim extracted from the Hymos database for the period 01-10-1999 to 30-09-2000 were used
- The location of the river bifurcation at Caronal and profiles for this river bifurcation were estimated
- A shapefile based on a recent satellite image with the exact location of the river Taquari following the drainage pattern from the DEM. The eastern reach of the lower Taquari river was not used in the 1D model.
- For the 'wet', 'dry' and 'average' scenarios discharge data at Coxim were used.

2D part of the model

In this section the input parameters, which will apply for the whole model, will be described. The following data was used for 1D2D model:

- The time step used for simulation is 30 minutes for the hydrological year 2000 (01-10-1999 to 30-09-2000)

- A series with precipitation and evaporation extracted from the Hymos database for the period 01-10-1999 to 30-09-2000 was inserted into the model.
- For the meteorological parameters wind, temperature and radiation the default values were used, because in this case they do not influence the results.
- The initial water level in 1D channels was set to 1 metre
- The method used for interpolating between successive cross-section locations is set to 'interpolation bank levels'
- The method used for calculating the flow of water from the 1D channel to the 2D grid is set to 'assume highest level of embankments'
- An initial infiltration capacity for the whole grid area is set to 5 cm
- GIS output for water levels, water depth and velocity is generated for every 30 days (more or less each month)
- A DEM with cell size 900 * 900m was used (based on a 90 * 90m grid created by ITC)
- A grid with hydraulic roughness values was used (based on a vegetation map made by Alterra)
- For the 'wet', 'dry' and 'average' scenarios, precipitation data and evaporation data were used.

Digital elevation model

Ben Maathuis from ITC created a digital elevation model from data from the SRTM 2000mission (Chapter 3). The digital elevation model was corrected for drainage and vegetation. The resolution from the resulting elevation model was 90*90metre. For the first SOBEK model the resolution from this elevation model was too fine, resulting in a very long simulation time. Accordingly, using the mean elevation from each hundred grid cells, a coarser grid with a resolution of 900*900metre was created.

Map with hydraulic roughness

The first grid with hydraulic roughness was based on a shapefile with vegetation types. The shapefile was classified into six different vegetation groups. Data from the satellite image from the dry period were put on top of the vegetation shapefile and a grid with a cell size of 900 * 900m was created (see Figure 4.25

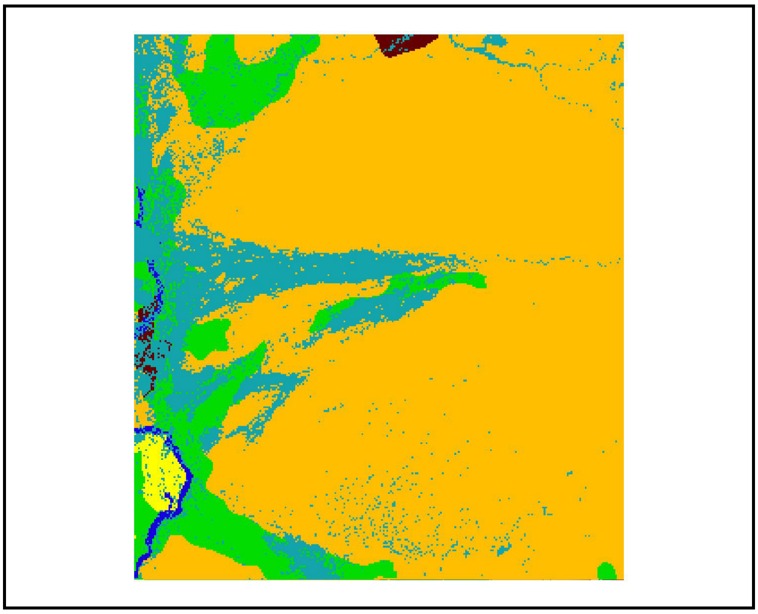

Figure 4.25 Grid with hydraulic roughness values; orange = 1m; dark blue = 0.003m; green = 1.5m; yellow = 0.4m; grey = 0.1m; dark brown = 5m and the value 4 is not on the map.

An improved vegetation map from Alterra was used in a later version of the model. This vegetation map had a resolution of 90*90m. This improved vegetation map shows more spatial variation than the first vegetation map (see Figure 4.26). The spatial variation was necessary for improving the distribution of inundated areas.

The vegetation map was converted to a map with hydraulic roughness (Nikuradse-values) using the values as listed in Table 4.1. The roughness of the different vegetation types were derived form a handbook of hydraulic roughness for Dutch river systems. Pictures showing the different vegetation types have been compared with pictures of the vegetation in the Pantanal and similar roughness values have been used.

Table 4.1 Hydraulic roughness (Nikuradse) values for each vegetation type

no.	vegetation type	Hydraulic roughness (m)	Handbook type (h = 1 m)
1	gallery forest	7.0	zachthoutstruweel
2	(semi) deciduous forest	7.0	zachthoutstruweel
3	form. pioneer (transição)	5.0	zachthoutstruweel
4	savannah forested (cerradão)	6.0	doornstruweel
5	savannah arboreal (cerrado)	3.0	droge ruigte + 10%
6	savannah gramineous lenhosa	4.0	riet
7	savannah gramineous lenhosa + arboreal	3.5	average of 5 and 6
8	pioneer vegetation	1.5	homogene natte ruigte
9	area cultivated	0.8	verruigd grasland
10	Baías	not present	
11	Corixo	not present	
12	Oxbow	not present	
13	Salina	not present	
14	Vazante	not present	
15	River	0.05	waterbodem (plas)
16	bare soil	not present	

Source: Stromingsweerstand vegetatie in uiterwaarden. Deel 1 handboek versie 1-2003. E.H. van Velzen, P. Jesse, P. Cornelissen and H. Coops. RIZA rapport 2003-028, Arnhem.

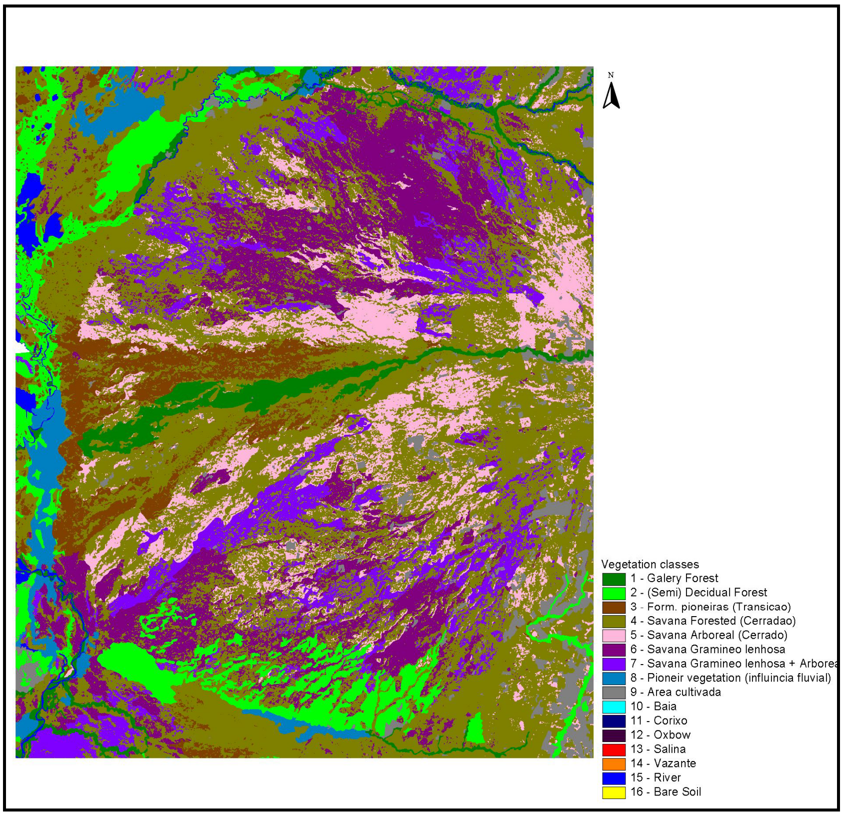

Figure 4. 26 Improved vegetation map from Alterra

Thereafter the grid was aggregated to a grid with a resolution of 900*900m using the median value. A comparison from three methods (median, mean and maximum) showed that the method with median values gave the most similar pattern with the original grid. The method using the median values resulted in the map with hydraulic roughness as shown in Figure 4.27.

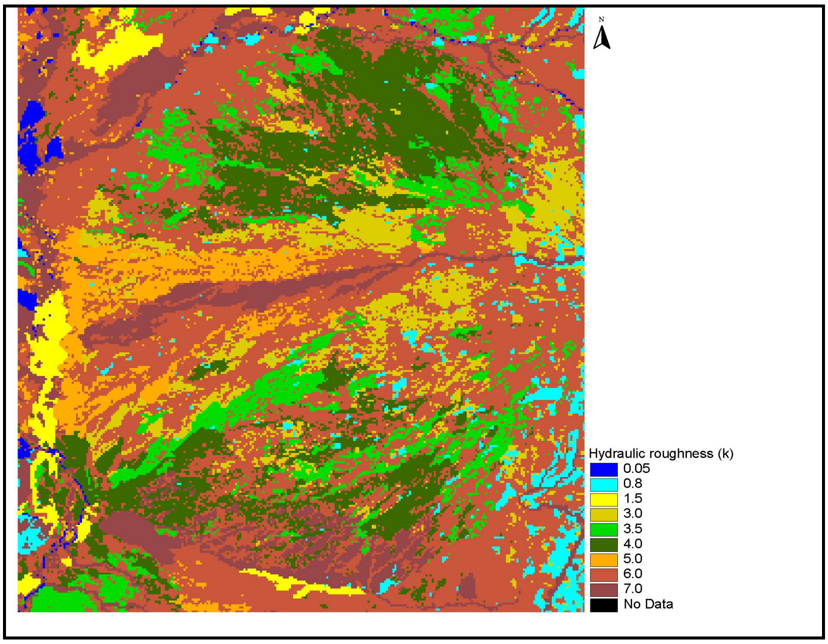

Figure 4.27 Map with hydraulic roughness values derived from improved vegetation map

4.7 Calibration

For the calibration of the SOBEK model data, for the hydrological year 2000 (01-10-1999 to 30-09-2000) have been used. SOBEK can be calibrated using many different parameters. For the calibration of the model it is common to use the parameters, which are the most uncertain. In this case it is hard to say which parameters are the most uncertain. The parameters hydraulic roughness and the infiltration capacity have been chosen based on experience with previous models.

The values used for the hydraulic roughness have been based on a handbook for vegetation roughness for Dutch river systems. The vegetation types described in this handbook are compared with the vegetation classes on the map of the Pantanal region, using photographs and descriptions. For each vegetation type the value for the hydraulic roughness can vary within a certain range, depending on, among other things, the depth of inundation, flow direction, season, age of vegetation and the variation within a vegetation type. Within the range for a certain vegetation type the values are changed during calibration. The spatial pattern of the vegetation types has not been changed.

The infiltration capacity of the soil is varied within the range possible for wetlands based on expert judgement. This parameter is spatially homogeneous. The range of the values used in the calibration is 1 to 15 centimetres. Due to the current availability of data it was possible to calibrate the model in two ways:
Calibrate (validate) on spatial distribution of flooded areas.
Calibrate on the discharges at Porto Esperança (the downstream boundary of the model)
Maps showing the spatial distribution of inundated areas were available for the dry as well as the wet season. These maps were derived from satellite data for the year 2003. The

spatial pattern of these maps can be compared with the spatial pattern on the maps generated during the SOBEK calibration run at the same moment (see Figure 4.28). The input parameters can be changed in a way that the spatial pattern of the resulting inundation maps from SOBEK is similar to the maps derived from satellite data. An improved vegetation map with more spatial variation was used to change the pattern of the inundated areas, but the results were not promising, the spatial pattern of the inundations did not change sufficiently to improve the calibration.

Figure 4.28 shows the inundated areas derived from satellite data in red and the inundated areas from the SOBEK simulation in blue. The drainage pattern on both images are similar, but the image from the satellite shows much larger inundated areas especially in the middle of the image around the river Caronal and around the lower end of the Taquari and in the northwest side of the image. The water that causes the inundation along the Caronal and Taquari in the satellite image is directly drained to the main channel in the SOBEK-model and induces very high discharge peaks. Only two parameters can influence the way the water flows outside the river channels, the hydraulic roughness (vegetation types) and the elevation model. Changing the hydraulic roughness has some influences on the velocity of water flowing through the model, but in this case it cannot induce large inundations as shown on the satellite image. It is very well possible that using the drainage pattern to create river channels in the elevation model and later on aggregating it to a 900*900m grid caused the problem. The dimensions of the channels in the aggregated elevation model are too big. This results in fast draining of the area, which is not realistic.

The observed discharges at Porto Esperança were obtained from the Hymos database. Observed discharges for the hydrological year 2000 were not available, so these discharges were created using the observed water levels of the hydrological year 2000 and the relation between discharge and water levels obtained from the historical dataset in Hymos. The 'observed' discharges are compared with the computed discharges at the branch just upstream of Porto Esperança.

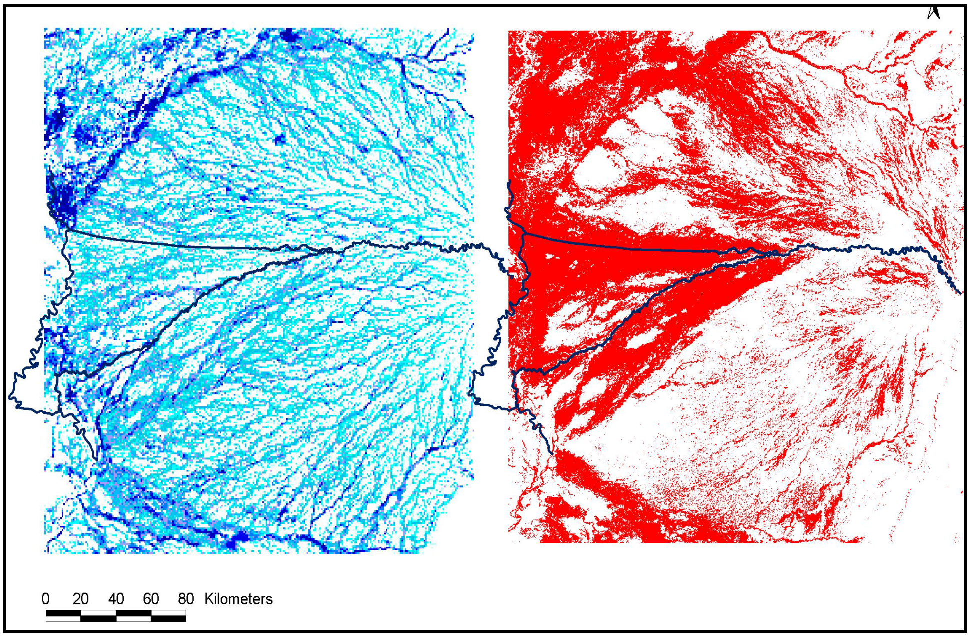

Figure 4.28 Comparison of simulated inundated areas from the calibration run (left) with satellite data from April 2003 (right)

At first the discharge at Porto Esperança was much too high and the peak of the discharge was in March instead of May or June. During the calibration process the infiltration capacity and the hydraulic roughness have been increased to decrease the amount of discharge and to delay the peak. Increasing the hydraulic roughness lowers the velocity of water flowing over the surface. As a consequence, the accumulation of water in the river channels will be delayed. Increasing the infiltration capacity will decrease the availability of water in the first months of the hydrological year, which is common in wetlands where at the start of the wet season the first amount of precipitation will infiltrate into the soil.

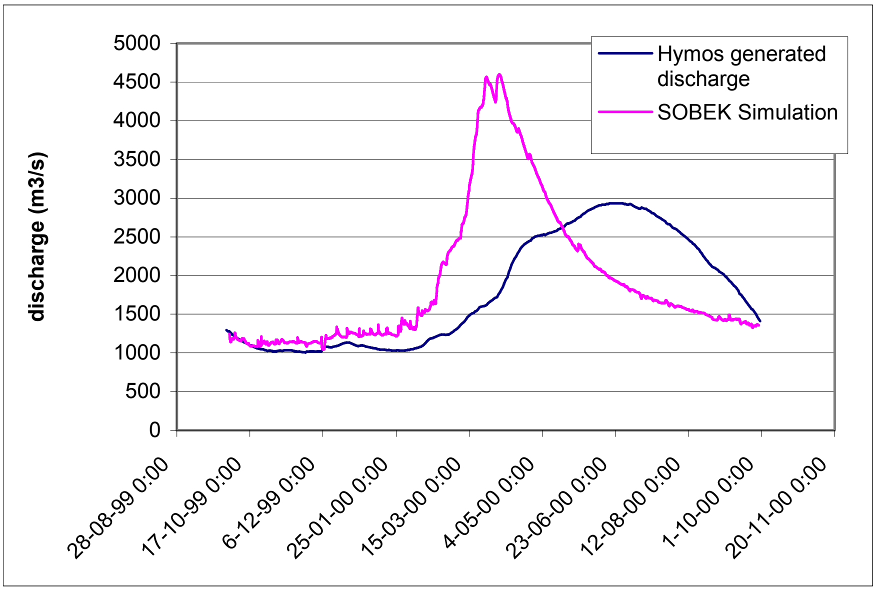

Figure 4.29 Simulated discharge with SOBEK and the generated discharge with Hymos at Porto Esperança.

Figure 4.29 shows the still poor results of the calibration. The peak of the discharge is still too high and it is in March instead of in May. Currently the water accumulates too fast in the main channels. The travel time to these main channels should be longer. It is possible that in reality more water infiltrates in the bottom and drains to the river in the subsurface layer in which the flow velocities are much smaller. There are still more parameters that can be optimised and the current dimensions of the network can be changed, but therefore it is necessary to have more data on more locations to calibrate on.

4.8 Results of scenarios

Three scenarios were created to make three alternative runs with the SOBEK-model. These alternative runs will give an idea about the observed extremes based on a historical dataset that the natural system has to deal with. The scenarios are (1) a 90% dry year, (2) average year and (3) a 90% wet year.

The 90% dry year is a hydrologically synthetical year in which for each time step 90% of the time steps at the same date in the historical dataset are wetter. For the 90% wet year it means of course that 90% of the time steps at the same date are drier. The results are given in Figure 4.30. It is clear that the simulated discharges for the three scenarios show a large variation in the wet season. The discharges simulated in the wet scenario are higher than the highest observed value in the historical database. Further calibration with extended data is necessary.

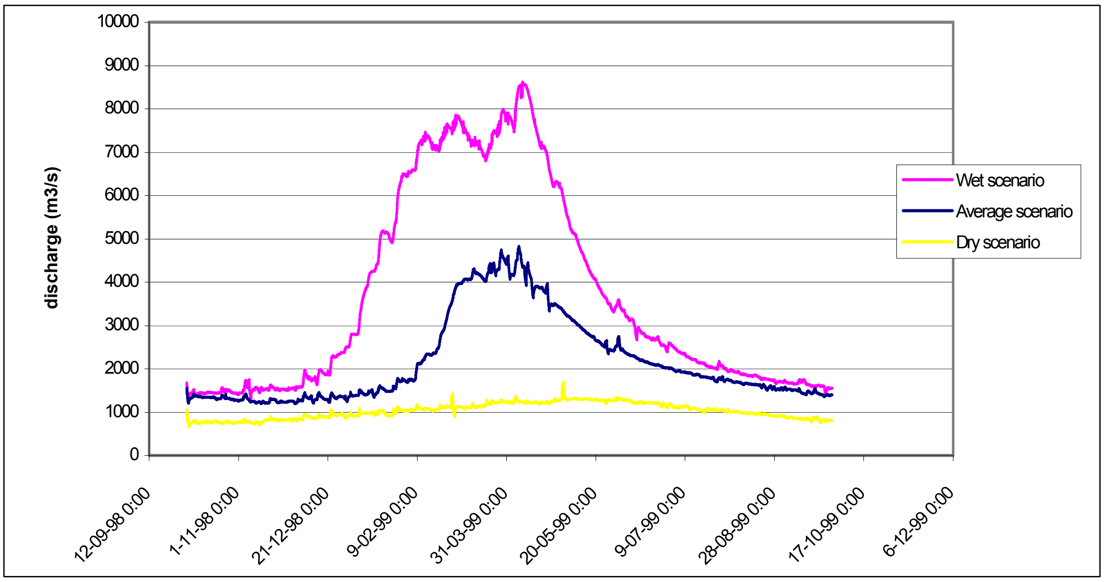

Figure 4.30 Simulated discharges for the three scenarios just upstream of Porto Esperança.

Maps of the inundated areas for the 27th of March (during the wet-season) in all the three scenarios are presented in Figure 4.31, Figure 4.32 and Figure 4.33.

Figure 4.31 shows the map of the inundated areas in the ‘dry’ scenario. In this scenario there are almost no large inundated areas through the whole year. In this scenario the water accumulates in the smaller channels in the drainage pattern superimposed on the elevation model.

Figure 4.32 shows the map of the inundated areas in the ‘average’ scenario. In this scenario more river channels have developed and some larger areas, mainly in the northwest and west side of the Pantanal, have been inundated. In the southern area a large river channel has been formed.

In Figure 4.33 the simulated inundated areas for the ‘wet’ scenario are presented. Compared with the other scenarios larger areas have been inundated. The water level in the inundated areas is higher and even more small river channels have been formed. But also in this scenario a large inundated area around the Caronal river, as can be seen on the satellite image, has not been formed.

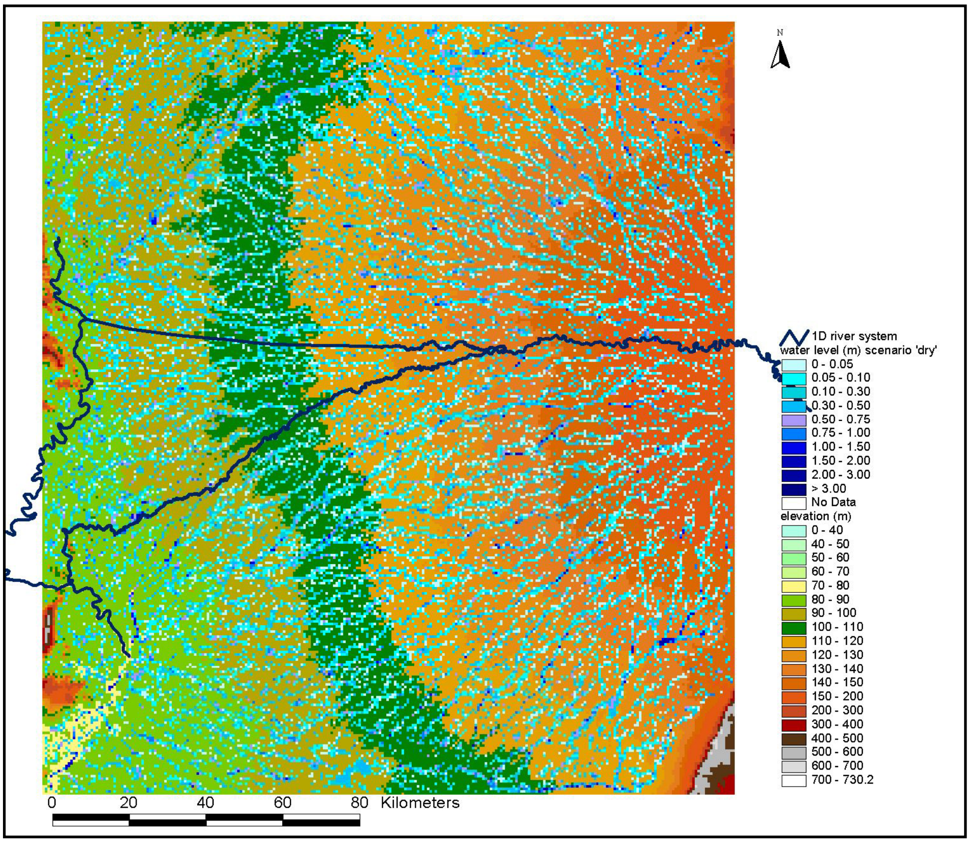

Figure 4.31 Simulated inundation areas for the 'dry' scenario

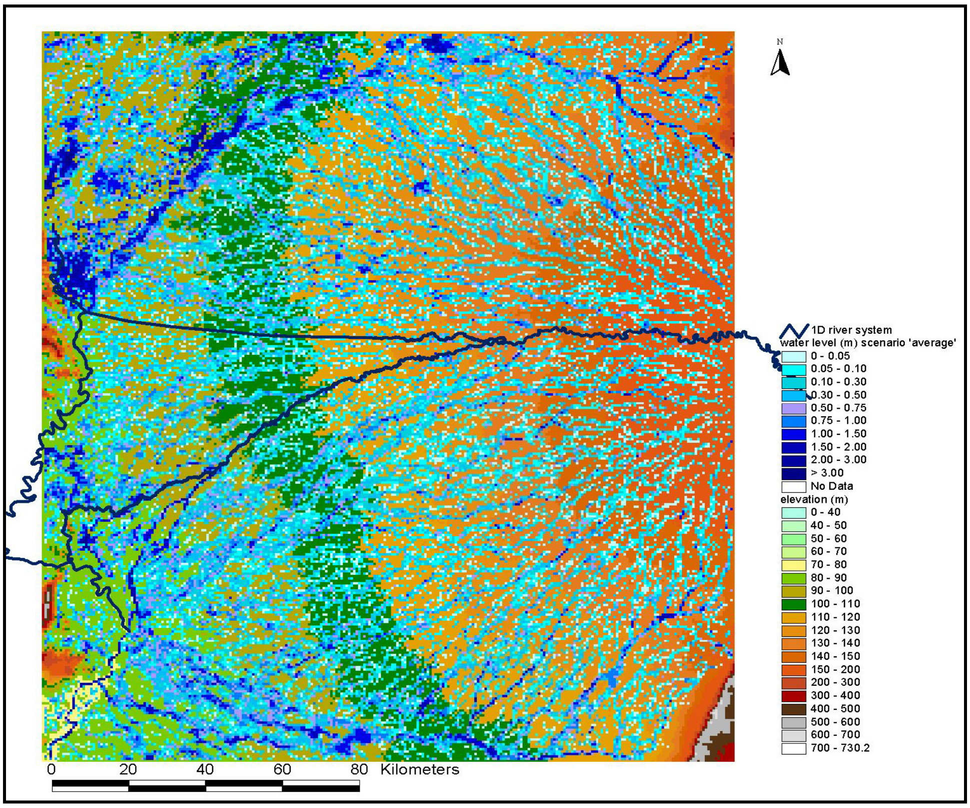

Figure 4.32 Simulated inundation areas for the 'average' scenario

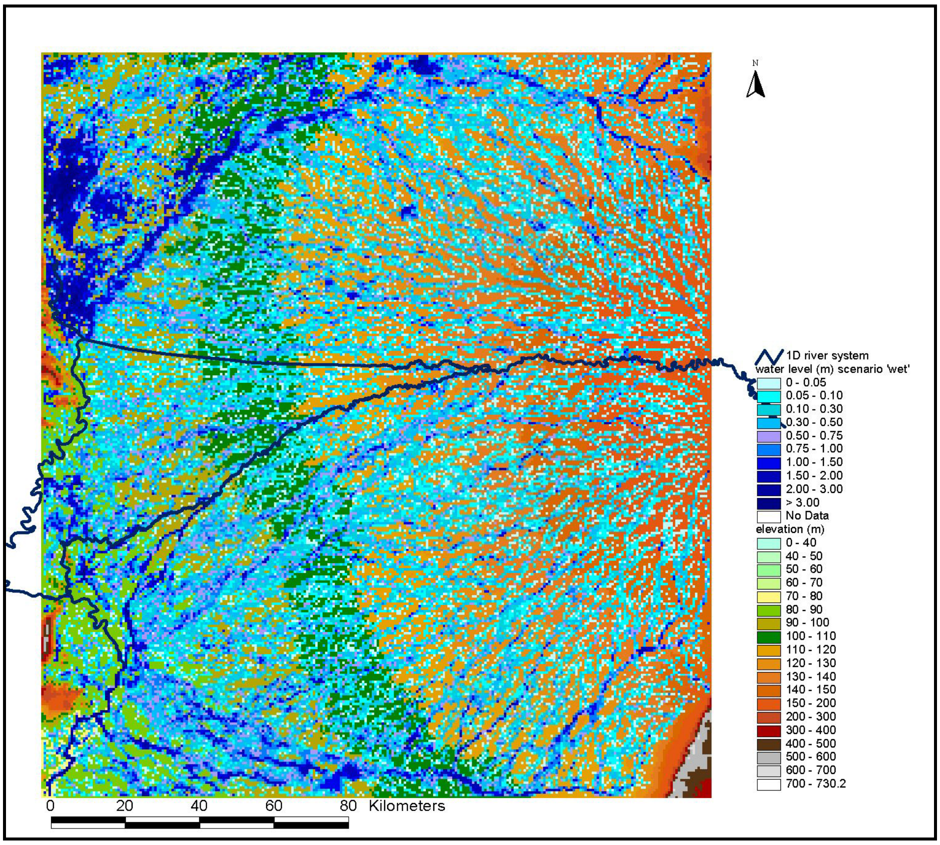

Figure 4.33 Simulated inundation areas for the 'wet' scenario

4.9 Conclusions

The results of the hydro-meteorological data processing suggest that recent years are substantially wetter than the 1970s. The correctness of the data still needs to be ascertained, but the consistent similarity in trends from different hydrographic stations indicates that these trends cannot be explained from local errors. This is a potentially important result that will play a role in obtaining further insight in the functioning of the Pantanal and the problems experienced by the farmers in the area. Further in depth statistical analysis is recommended to substantiate this conclusion.

A combined one-dimensional and two-dimensional model has been set up in SOBEK. The computed spatial distribution of inundated areas resembles the distribution on satellite images, although there are still large differences, in particular in the north western and western zones of the model domain, where large inundated areas are not reproduced by SOBEK. Furthermore, the discharges are not reproduced well. Discharge peaks are too high and arrive too early (April instead of May-June). The discrepancies can be ascribed to two major causes:

1. The channels of the drainage patterns have become too wide or too deep during the pre-processing of the DEM by ITC. It is recommended to optimize this pre-processing on the basis of cross-sectional data and SOBEK model runs;
2. The spatial pattern of large inundated areas in the north western and western zones of the model domain depends sensitively on the topography and bathymetry of the area around the Caronal bifurcation. It is recommended to carry out a more detailed topographic and bathymetric survey in this area.

Nonetheless, the present model does provide insight in the extreme variations that the natural system has to deal with. This insight has been obtained by making computations for wet-year, ordinary-year end dry-year scenarios that had been derived from a historical dataset.

5 Flooding and sedimentation

Chris Stolker[10] *and Erik Mosselman*[11]

5.1 Introduction

This chapter has been accomplished after a field mission in the Pantanal and in particular in the Taquari area (March 30th to April 4th 2004) within the framework of the Pantanal–Taquari project. It reports river data and information obtained during the river survey as well as an assessment of sedimentation and flooding problems of the Rio Taquari in the Pantanal. The chapter has been written by mr. C. Stolker and E. Mosselman. Arc-View assistance was provided by mr. G. Groenveld (Alterra) and mr. M. Ververs (WL | Delft Hydraulics).

Measurements of the following river aspects between Coxim and Corumbá were carried out during the river survey.

1. Sonar measurements of the water depth in the vicinity of the river thalweg (e.g. the deepest locations along the river).
2. Grab samples of the channel sediment.
3. Sonar measurements of 26 perpendicular cross-sections (including sketches of the banks above the water level).
4. DGPS point measurements of the water level at 9 locations along the Rio Taquari, the Caronal and the Paraguai River and at one geographical known position in Corumbá;
5. GPS flow velocity measurements in the thalweg.

These data have been worked out into:

- The longitudinal profiles of the thalweg depth, the bed level and the water level
- The longitudinal profile of the characteristic grain sizes of the river bed sediment
- The longitudinal profile of the approximated flow velocities in the vicinity of the thalweg
- A total of 26 cross-sections in the Rio Taquari and the New Caronal.

5.2 Longitudinal profiles of water level, bed level and thalweg depth

The field expedition was carried out with a small open boat using an outboard motor. An acoustic sonar device was placed 0.3 m below the water surface and was attached to the boat. During the first two days of the trip, the distance between the sonar and the river bed was measured with a frequency of 0.1 Hz and during the following days with a frequency of 0.5 Hz. Both the measured depth and the geographical position of the boat in X, Y co-ordinates were stored on a disk.

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Water depth and water level

between the various depth points enables the production of a longitudinal profile of the water depth in the Rio Taquari (Figure 5.1) and in the upstream part of the New Caronal (Figure 5.2).

Although, the presented longitude (X) and latitude (Y) geographical position of a common GPS is quite accurate, the delivered altitude (Z) is very unreliable (> 10m). However, an accurate altitude level of the water surface along the river was important to determine the actual bed level. That is why DGPS measurements of the water level have been carried out at 9 locations along the river. One DGPS-measurement of a geographical known point in Corumbá showe All data has been imported in ArcView. A fluent sailing path was drawn through the measured depth points, and redundant points were removed. Due to shallow water depths in the Rio Taquari the boat was continuously following the deepest sections of the river. Therefore, this sailing path can more or less be seen as the river thalweg (e.g. the deepest locations along the river stretch). The cumulative distance d an accuracy of the DGPS measurements within 0.1 m. The DGPS levels show a rather constant gradient in water lever in a large part of the Taquari. Therefore, a linear interpolation between the various DGPS measurements seems to be allowed. The observed water depths have been related to this obtained water level and are presented for the Rio Taquari in Figure 5.3 and for the upstream part of the New Caronal in Figure 5.4. The corresponding discharge of this period has still to be requested at the administrating organization.

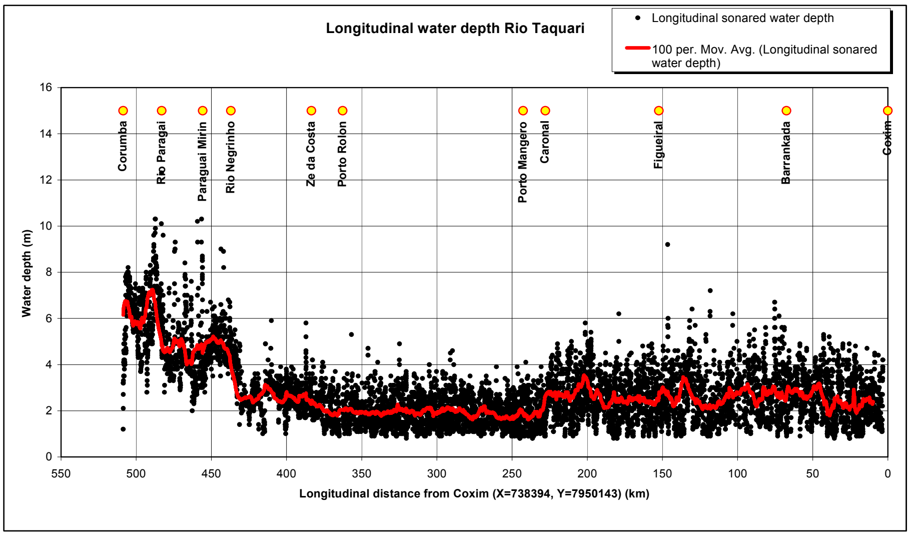

Figure 5.1 Longitudinal profile of the water depth along the thalweg in the Rio Taquari (March 30th to April 4th)

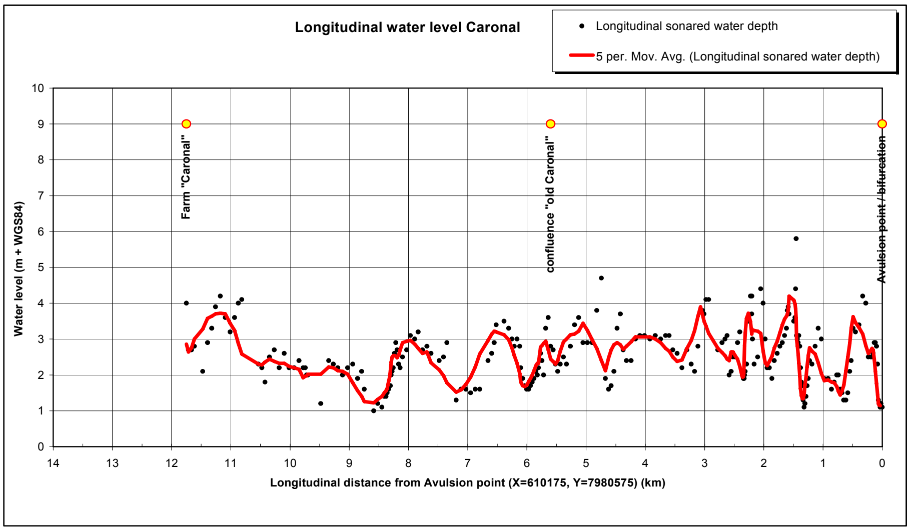

Figure 5.2 Longitudinal profile of the water depth along the thalweg in the New Caronal (March 30th to April 4th)

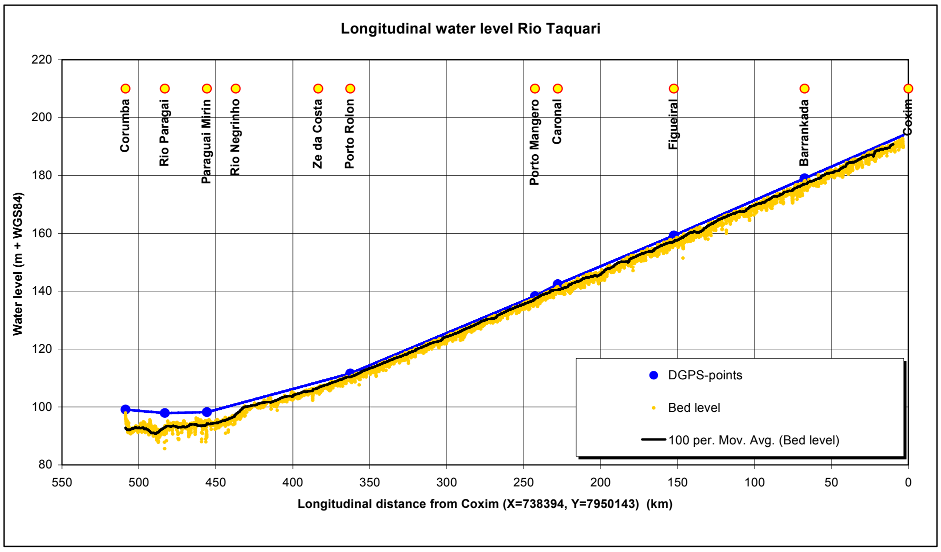

Figure 5.3 Longitudinal profile of the water level and the bed level along the thalweg in the Rio Taquari (March 30th to April 4th).

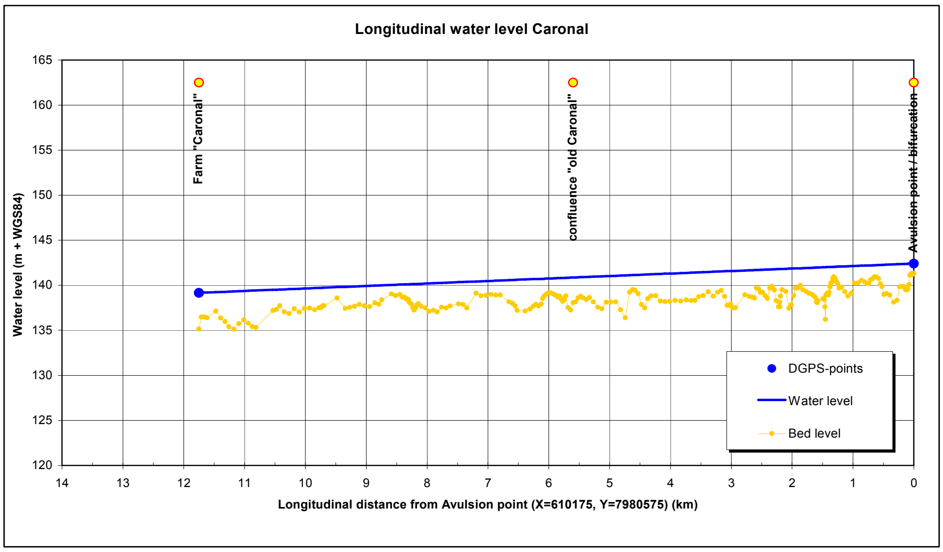

Figure 5.4 Longitudinal profile of the water level and the bed level along the thalweg in the New Caronal (March 30th to April 4th)

The previous figures together with field observations lead to the following conclusions:

- In the major part of the Taquari the water depth varied between a few dm and 5 m (except for some points and downstream of the Rio Negrinho).
- The average water depth in the lower Taquari downstream of the New Caronal avulsion (rkm 225– 425) is approximately 1 m lower than the upper part of the Taquari.
- Downstream of rkm 425 the water depth increases considerably (up to 200%) and varies between 2 and 10m.
- The water depth in the 12 km long upstream part of the New Caronal varies between 1 and 4 m.
- The water slopes that have been observed are given in Table 5.1
- The slope in water level between Coxim and Zé da Costa is very constant.
- The slope in water level in the upper part of the New Caronal is slightly steeper than the slope of the lower Taquari.

Table 5.1 Water level slope (measurements March 30th to April 4th)

River	**Section**	**rkm in figures**	**water level slope (m/km)**
Rio Taquari	Coxim – Caronal	0 – 228	0.229
	Caronal bif. – Porto Rolon	228 – 363	0.229
	Porto Rolon – Paraguai Mirin	363 – 456	0.144
	Paraguai Mirin – Rio Paraguai	456 – 483	0.011
Caronal	bifurcation – Farm :"Caronal"	0 – 12	0.277
Rio Paraguai	Corumbá – Rio Taquari	456 – 483	0.017

5.3 Longitudinal distribution of characteristic grain sizes of the river bed sediment

Along the river stretch 17 samples of the river bed material have been obtained, using a Van Veen grabber of approximately 5 litre (Figure 5.5).

Figure 5.5 Van Veen grabber used for taking the grab samples during the River Survey

The sediment samples were sieved in the laboratory of Embrapa. From this analysis accumulated sieve curves have been developed, which are presented in Figure 5.6. The actual sieve diameter of the particles was determined as follows: if a particle falls through sieve D_A and remains on the next sieve D_B then the actual sieve diameter $D = (D_A * D_B)^{1/2}$.

Table 5.2 provides for each sample the characteristic grain sizes: D35 (35% of the sediment is smaller), D50 (50% of the sediment is smaller, median grain size), the mean grain size diameter Dm and D90 (90% of the sediment is smaller), in which Dm is defined as:

$$Dm = \frac{\sum (p_i \cdot d_i)}{\sum p_i} \qquad (5.1)$$

Table 5.2 also provides the geographical location (X and Y) of the samples obtained.

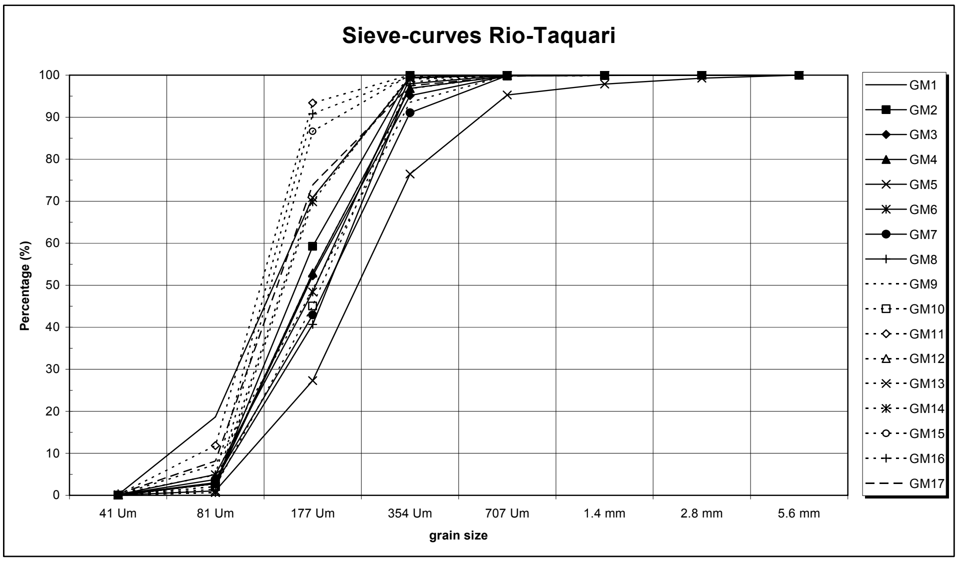

Figure 5.6 Accumulated sieve curves of the river bed samples

Table 5.2 Characteristic grain sizes (in mm)

Sample	X (m)	Y (m)	Location	rkm	D35 (mm)	D50 (mm)	Dm (mm)	D90 (mm)
GM1	725918	7960601		22.9	0.111	0.139	0.212	0.295
GM2	715167	7963669		40.3	0.136	0.161	0.246	0.310
GM3	707229	7973740		67.4	0.144	0.172	0.276	0.333
GM4	692064	7983131	Cross-section TK5	105.5	0.143	0.171	0.269	0.326
GM5	665750	7984055	Figureial	152.4	0.204	0.258	0.554	0.608
GM6	632303	7984084	Cross-section TK6	197.4	0.147	0.182	0.266	0.321
GM7	617485	7982093	Cross-section TK9	218.3	0.157	0.203	0.307	0.350
GM8	599183	7979075	Cross-section TK10	241.7	0.162	0.206	0.286	0.329
GM9	610483	7980605	upstream Caronal bifurcation	227.5	0.145	0.181	0.283	0.340
GM10	600631	7981404	Caronal avulsion		0.154	0.193	0.278	0.326
GM11	579837	7974744		268.1	0.108	0.126	0.177	0.173
GM12	556887	7966060	Cross-section TK11	302.5	0.143	0.171	0.269	0.326
GM13	518037	7942817	Porto Rolon	362.6	0.127	0.148	0.230	0.297
GM14	502615	7930932	Ze da Costa	387.1	0.129	0.149	0.230	0.295
GM15	493109	7928593	Bifurcation point	400.1	0.119	0.136	0.199	0.221
GM16	466581	7917417	Rio Negrinho	437.5	0.115	0.131	0.190	0.176
GM17	453752	7913038	Paraguai Mirin	463.2	0.120	0.142	0.226	0.298

Characteristic grain sizes along the river

The sediment can be characterized as fine sand, which indicates that the dominant transport mechanism of the sediment is suspended load transport (transport of particles moving in the fluid and kept in suspension by turbulent diffusion).

The grain sizes do not vary strongly in downstream direction, as can be seen in Figure 5.7, which presents the longitudinal distribution of the characteristic grain sizes, although minor downstream fining can be noticed.

The critical flow velocity for this sediment mixture is approximately 0.35 m/s, which is the point of initiation of motion of the sediment particles.

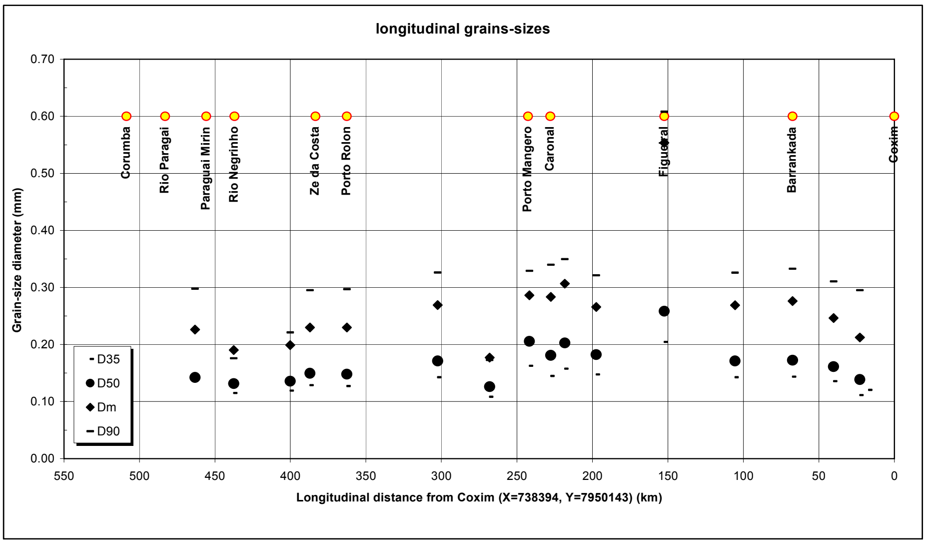

Figure 5.7 Longitudinal distribution of the grain sizes

5.4 Flow velocities

GPS flow measuring

Although a sophisticated flow velocity measuring device was not available during the field trip, the flow velocity at the water surface (U_{wl}) has been determined in a straightforward way. The engine of the boat was turned off and the boat drifted with the speed of the water, approximately along the river thalweg. The corresponding speed was read from the GPS and was corrected upwards or downwards if floating particles on the water surface were travelling faster of less fast than the drifting boat. This technique was repeated at various locations along the river.

Determination of the depth-averaged flow velocity

The flow velocity at the water surface has been re-calculated to the depth average flow velocity U, using the following equation:

$$U = \frac{U_{wl}}{\ln\left(\frac{h}{z_0}\right)}\left[\ln\left(\frac{h}{z_0}\right) - 1\right] \qquad (5.2$$

The measured values of flow velocity, flow depth and gradient result in a remarkably low hydraulic roughness. Therefore, the depth-averaged flow velocity is calculated using theoretical relations for hydraulically smooth beds. Parameter z_0 is the level of zero velocity or discharge, which, in case of a hydraulically smooth surface can be determined by the following equation:

$$z_0 \approx \frac{\delta}{117} \tag{5.3}$$

where δ denotes the viscous sub-layer at the bottom defined by:

$$\delta = 11{,}6\frac{\nu}{u_*} = 1.6\frac{C}{\mathrm{Re}\sqrt{g}}h \tag{5.4}$$

The other symbols are explained in the list of symbols on page I-ii.

The basis of equation (5.2) is the assumption that the water velocity in vertical or depth direction can be described by a logarithmic velocity distribution, with:

$$u(z) = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right) \tag{5.5}$$

Equating the integral along the water depth of equation (4.4) to the depth-averaged flow velocity U times the water depth h, and the flow velocity at the water surface $u(z) = U_{wl} = u(h)$ and assuming $z_0/h<<1$, equation (4.4) can be rewritten into equation (4.1). This equation enables us to calculate the depth-averaged flow velocity with the flow velocity at the water surface U_{wl} as input.

Depth-averaged flow velocities along the river

The following figures show the distribution of the depth-averaged flow velocity U along the Rio Taquari (Figure 5.8) and along the upper part of the New Caronal (Figure 5.9). The depth-averaged flow velocity in the Rio Taquari varies between 0.3 m/s and 1.4 m/s. The flow velocity decreases in downstream direction. The flow velocity in the upper part of the Caronal is more ore less constant.

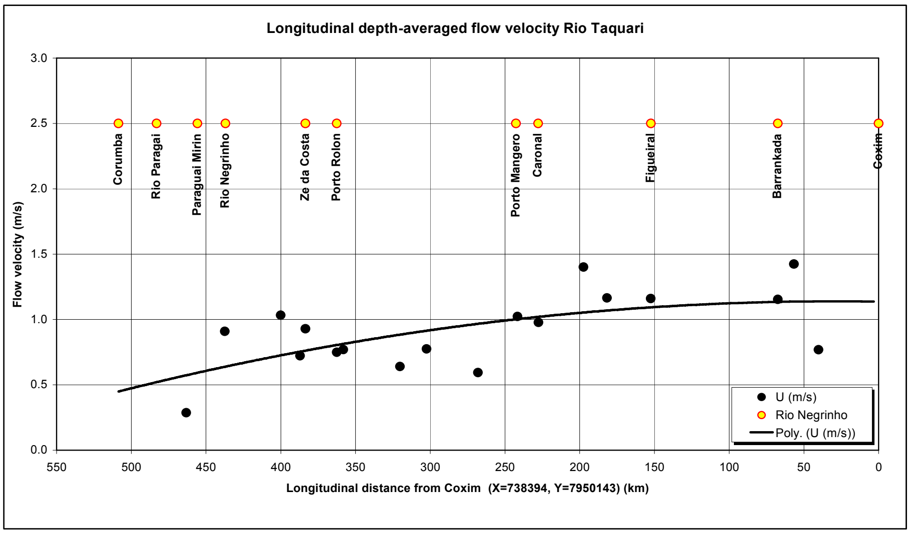

Figure 5.8 Longitudinal distribution of the depth-averaged flow velocity along the thalweg in the Rio Taquari (March 30th to April 4th)

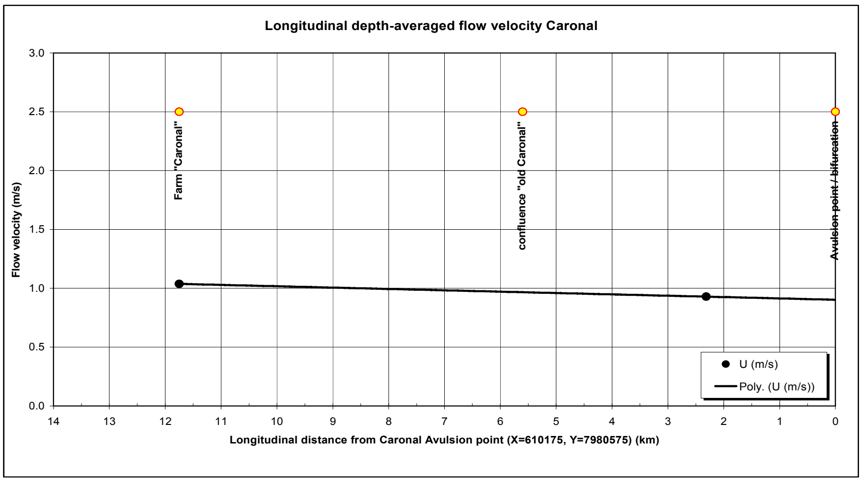

Figure 5.9 Longitudinal distribution of the depth-averaged flow velocity along the thalweg in the New Caronal (March 30th to April 4th)

5.5 Cross-sections

Besides the longitudinal measurements of the water depth, at 26 locations in the Rio Taquari and the Caronal the water depth was measured in sections perpendicular to the river axis in order to obtain representative cross-sections. Due to local circumstances the boat with the sonar was able to reach the river banks within one or a few metres. Therefore, for each cross-section a rough sketch was made of the left and right banks above the present water level. The dimensions of the banks were estimated.

Among other purposes, the newly measured cross-sections can be used for the following:

- record of the present local river width and river depth;
- examination of the morphological changes after the previous cross-sections surveys;
- record of the differences between cross-sections at bifurcations.

Between 1995 and 1997 also a set of cross-sections was measured in the Rio Taquari. During the field survey almost all of these cross-sections have been re-measured. The locations of the previous cross-sections are given in Table 5.3.

Table 5.3 Previously measured cross-sections

Name	X (m)	Y (m)	Altitude Z (m)	Date	Re-measured
TK3	721083	7959585	-	17-09-1995	no
TK4	710461	7970312	-	18-09-1995	yes
TK5	692084	7982830	-	19-09-1995	yes
TK7	655966	7984369	-	21-09-1995	yes
TK8	632299	7984080	-	23-09-1995	yes
TK9	617563	7981976	-	24-09-1995	yes
TK10	599183	7979075	-	25-09-1995	yes
TK11	556928	7965986	-	26-09-1995	yes
TK12	7942753.69	518086.62	-	1995	yes
Figueiral	665741.26991	7983813.42499	154.2	Jan 1997	yes
Pte. Velha - Coxim	739203.82288	7951022.82050	-	Jan 1997	no
Zé da Costa	505566.88841	7931723.79364	87,9	Jan 1997	yes
Pot. Rio Merino	466581.67160	7917487.92688	80,35	Jan 1997	yes
P. Mirin Faz. S. Bened.	453918.54138	7912946.51475	101,2	Jan 1997	yes
Figueiral	665741.26991	7983813.42499	154,2	Jan 1997	yes

The cross-sections have to be used with a certain reservation. They account only for the local situation and only for the date they were measured on. The Rio Taquari is characterized by strong cross-sectional variations (river width and depth) in longitudinal and perpendicular direction. The river and the cross-sections also vary strongly in time, due to all kinds of morphological processes.

Morphological development

The 26 measured cross-sections have been plotted in separate figures and can be found in Appendix A (Cross-sections in the Rio Taquari) and in Appendix B (Cross-sections in the Caronal). The morphological development at certain cross-section locations is tried to determine by comparing the previous and present measured cross-section at a corresponding location. Twelve cross-sections have been re-measured after they were first measured 7–9 years ago (1995 - 1997).

Table 5.4 presents an analysis of the differences in corresponding cross-sections. For these profiles the new as well as the previous cross-section were appended to the respective figures in appendix A, which facilitates the comparison and the finding of mutual differences. The vertical change in bed level is almost impossible to determine as it seems that the altitude between the '95-'97 cross-sections and the present ones differ eminently. However, the shapes of the cross-sections have often remained similar, which also indicates that the correct locations were sonared. By shifting the '95–'97 cross-sections to the present ones (the new cross-sections are probably more reliable), the horizontal differences could be assessed.

Table 5.4 Indication of morphological changes at cross-section locations

Name	Figure	Vertical change		Transversal change			
	Appendix A Separate report	Sedimen-tation (m)	Erosion (m)	Shifted Left >10m	Shifted Right >10m	Widened (m)	Narrowed (m)
TK4	A-1	unknown[1]	unknown[1]	yes[2]	no	no	no
TK5	A-3	Probably	unknown[1]	yes	no	no	15
Figueiral	A-1	unknown[1]	unknown[1]	no	no	25	no
TK7	A-6	unknown[1]	unknown[1]	yes	no	10	no
TK8	A-7	unknown[1]	unknown[1]	yes	no	no	40
TK9	A-8	unknown[1]	unknown[1]	yes	no	20	no
TK10	A-11	unknown[1]	unknown[1]	no	no	15	no
TK11	A-13	unknown[1]	unknown[1]	no	no	15	no
TK12	A-15	unknown[1]	unknown[1]	yes[2]	no	no	40
Zé da Costa	A-16	unknown[1]	unknown[1]	no	no	15	no
Rio Negrinho	A-20	unknown[1]	unknown[1]	no	no	15	no
Para. Mirin	A-21	unknown[1]	unknown[1]	no	no	no	no

1 All the re-measured cross-sections lay on a higher level than the previous measured cross-sections. The most straightforward explanation is a difference in reference-level. The altitude of the present cross-sections has been determined with a DGPS, of which the coordinates are referred to the WGS84 geoide. The altitude of the 1995 – 1997 cross-sections has probably been referred to an older or other system. Unless the difference between these systems is discovered, conclusions about sedimentation and erosion of the cross-sections are almost impossible to make.

2 This is a typical bend cross-section, with a shallow inner bend and a deep outer bend. According to the measurements the cross-sections are shifted in the direction of the inner bend. This is unusual and probably not right because rivers mainly displace by enlarging their outer bend, unless there has been a matter of cut-off.

5.6 Flooding and sedimentation

Certain farm lands that were once dry during part of the year, are flooded more or less permanently since 1974. This has severe impacts on the economic viability of the farms. Remarkably, this unfortunate situation seems to have been created during a single large flood in 1974. The area never recovered from that. Farmers observe that the Río Taquarí in that area is now much shallower than before 1974 and, therefore, ascribe the flooding problems to sedimentation. However, the precise causes of the flooding and the sedimentation are not clear.

The lower course of the Río Taquarí lies on a huge alluvial fan that consists of material eroded from the upstream Planalto. Further sedimentation is hence only natural and the present ecosystem has adapted to that (Present average sedimentation is of the order of 0.04 mm/year, derived from PCBAP information that the present average sedimentation is of the order of 100 ton/(km^2·year)). Problems arise, however, when sedimentation accelerates to such an extent, that it affects the ecosystem or hampers economic activities. Such acceleration may actually be the case since changes in land use on the upstream Planalto have enhanced the erosion of the Planalto and hence the sediment yield to the Rio Taquari.

The sediment transport in the river can be divided into bed-material load (= bedload + suspended load) and washload. The bed-material load consists of sands and contributes to sedimentation on the river bed as well as on terrains close to the river (natural levees). This sedimentation produces the lobes that are a central element in the evolution of alluvial fans. Accelerated sedimentation might lead to an increased probability of avulsion within the next decades. The washload consists of fine materials (silt, possibly clay) and contributes to sedimentation all over the area in zones where slowly flowing or stagnant water bodies occur during and after a flood.

Sedimentation related to bed-material load manifests itself in vertical and horizontal morphological changes of the river.

Sedimentation related to washload manifests itself all over the areas of the Pantanal that are flooded annually with water from the Rio Taquari. The rates of this type of sedimentation can be inferred from an analysis of deposits as presented by Godoy et al. (2002). The data show that the sedimentation has accelerated after the 1970s. This may have an important effect on the ecosystem and therefore merits further research. However, the resulting aggradation seems too low for the creation of drainage obstacles that enhance the flooding of farm land. Deposits of bed-material load may also be spread over the full Pantanal by Aeolian transport (transport by wind).

Approach
Six hypotheses have been postulated to explain the causes of the sedimentation and flooding problems.

Hypothesis 1	The bed of the Rio Taquari experiences sedimentation due to sediment overloading upstream (Planalto)
Hypothesis 2	Hydrological variations in the river basin have led to higher discharges in recent years
Hypothesis 3	The water levels on the Rio Paraguai have become higher
Hypothesis 4	The distance to the Rio Paraguai has become longer
Hypothesis 5	The farm land is flooded by overland flow from elsewhere
Hypothesis 6	The river has become wider and more braided due to an extreme flood around 1974

Effect of sediment overloading from upstream

The first hypothesis is that the bed of the Rio Taquari experiences sedimentation due to sediment overloading upstream (Planalto). Three major sediment loads to the Rio Taquari can be distinguished:

1 The river transports bed material from its upstream reaches to downstream reaches.
2 A number of areas in the Planalto show signs of surface erosion (bare surfaces surrounded by vegetated areas). During heavy precipitation sediment particles can be released and washed away to eventually make it to the main river, although it is possible that the river will not be reached. If the river is reached this sediment is indicated as wash-load, due to its origin.
3 A third form of sediment supply to the river is caused by bank erosion. Especially in the upper part of the Rio Taquari between Coxim and the New Caronal avulsion, the river banks are heavily attacked by the flow, as is testified by the vegetationless steep slopes.

The following considerations explain why it is more likely that the major supply of sediment to the river is coming from the river banks and not from surface erosion on the Planalto:

- The number and sizes of the erosion areas in the Planalto, as being observed during the field survey, are far from large enough to explain an excessive sediment supply to the river. Furthermore, it is not expected that all the eroded sediment will eventually reach the river and if it does, there is often a large time lag between the moment of erosion and the arrival at the river.
- The eroded material from the Planalto is coming from the upper layers, which is the organic fertile humus. The particle sizes of this material are often small (between 50 μm and 70 μm). That is why it only settles in areas of stagnant or almost stagnant flow, which are the floodplain areas far from the flowing river, and why it does not contribute to the morphological processes in the river itself. Furthermore, the obtained grab samples along the flowing and morphologically active Rio Taquari seldom show signs of organic material.
- The bank erosion along the Rio Taquari, between Coxim and the Caronal avulsion, is extensive. Eroded material is deposited directly into the river. The bank erosion often occurs in the outer bends, of which a part of the eroded material will contribute to growth of the inner bends. As the outer bank is higher than the inner bend, a significant part of the eroded material will be added to the morphologically active river bed.

The sediment distribution at bifurcations is complex and often not in proportion to the transport capacity of the flows in each branch. A developing avulsion is a manifestation of an unstable bifurcation where one branch receives less sediment than it can transport and the other branch receives more sediment than it can transport (cf. Sloff et al, 2003; De Heer & Mosselman, 2004; Van der Mark, 2004). These processes should also hold for the Caronal bifurcation. Hence the dying old Lower Taquari experiences sedimentation, whereas the new Caronal branch has a larger flow depth that is not immediately accommodated by larger cross-sections. It takes time for the river to enlarge its cross-sections by erosion.

High sedimentation rates create bars and faster channel migration that is visible on aerial photographs and satellite images. The satellite images from different years, however, do not show such bars or faster channel migration.

In order to show the river area in which aggradation would have taken place as a result of sediment overloading from the Planalto, a straightforward 1D numerical model of the Rio Taquari based on the modelling system SOBEK of Delft Hydraulics was developed. The simulations show the large-scale bed level development of a sediment overload at Coxim, which will be migrating in downstream direction.

The bed and water level slopes as well as the grain sizes and the cross-sections were obtained from the parallel report on the Taquari River Survey. A constant discharge of Q = 200m^3/s was applied and the upstream (equilibrium) sediment load was increased with 10% with respect to the reference situation. Using the transport formula of Engelund & Hansen, the development of the aggradation in time was calculated over a period of 30 years (see Figure 5.10).

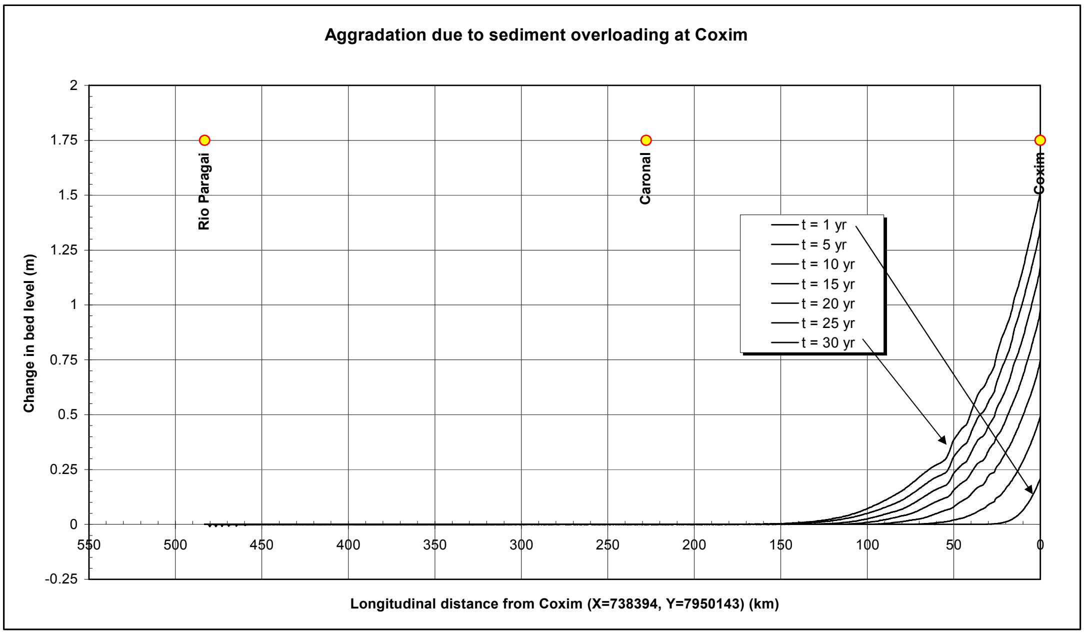

Figure 5.10 Aggradation due to sediment overloading at Coxim

The distance over which the aggradation extended in the simulation period of 30 years is on the order of 150 kilometres from Coxim. The Caronal bifurcation was not reached. It is, therefore, not likely that sediment overloading upstream of Coxim (Planalto) during the last 30 years can be the cause of the sedimentation and flooding problems in the lower reaches of the Taquari.

Effect of hydrological variations in the river basin

The second hypothesis reads: Hydrological variations in the river basin have led to higher discharges in recent years

The years 1963-1973 have been particularly dry. The previous period was wetter and the most recent period even wetter than that. Van Kappel and Ververs (2004) report periodical measurement of the last decades, which show that both the discharge and the water levels after 1974 have risen in the Rio Taquari (Measuring point at Coxim) and the Rio Paraguai (Measuring point at Amolar, São Fransisco and Porto Esperança). At Coxim the lower water levels would have risen with more than 1.5m, up to more than 2m at peak discharges (corresponding changes in discharge on basis of QH-curves: more than 100m^3/s for the lower water situations up to 600 – 1.400m^3/s at peak discharges). Also in the Rio Paraguai, at Amolar, the water levels would have risen between 1.25 and 3m (corresponding changes in discharge between 100 and 1,000m^3/s). At Porto Esperança in the Rio Paraguai the water levels would have risen between 1 and 6m.

Because it is likely that the rating curves are obtained from the water level measurements at certain gauge stations, by means of QH-relationships, there is a lack of two or more independent sources that prove water level rises as well as discharge increases at each location in the recent years. This is due to the fact that a rise in water level can be introduced by a (systematic or periodical) mistake in the water level measurements. However, the water level gauge stations at Coxim, Amolar, São Fransisco and Porto Esperança all show a rise in water level. It is unlikely that this is explained by measurement faults only. Furthermore, the rise of the water level at all these locations can almost only be explained by an increase in discharge. Therefore, it is likely that water levels as well as discharges have risen indeed.

From the precipitation data in the report of Van Kappel and Ververs (2004), it is difficult to find reliable evidence for a major increase in precipitation after 1974 due to limited data.

Effect of water levels on the Rio Paraguai

If the water levels on the Rio Paraguai are becoming higher, they push up the water levels on the Rio Taquari and its surrounding terrains ('backwater effect'). This underlies the third hypothesis: the water levels on the Rio Paraguai have become higher.

The previous section described the rise of the water levels and the discharge in the Rio Taquari and the Rio Paraguai in the last decades. The chapter showed that the water levels in the Rio Paraguai at the confluence with the Rio Taquari have probably risen with 1m up to 6m compared to the hydrological situation of 1974.

This downstream water level rise has a direct influence on the water levels in the lower Rio Taquari itself, due to back-water effects and associated sediment deposition. The effect that this rise of water level has in the Rio Taquari diminishes slowly in upstream direction (see Figure 5.11). The distance X upstream in the Rio Taquari, where the influence of the Rio Paraguai is negligible can be calculated with simple rules of thumb, more complex formulas or by means of a detailed numerical model. In general, a detailed numerical model will provide the highest accuracy, because it is capable of taking into account unsteady and non-uniform situations.

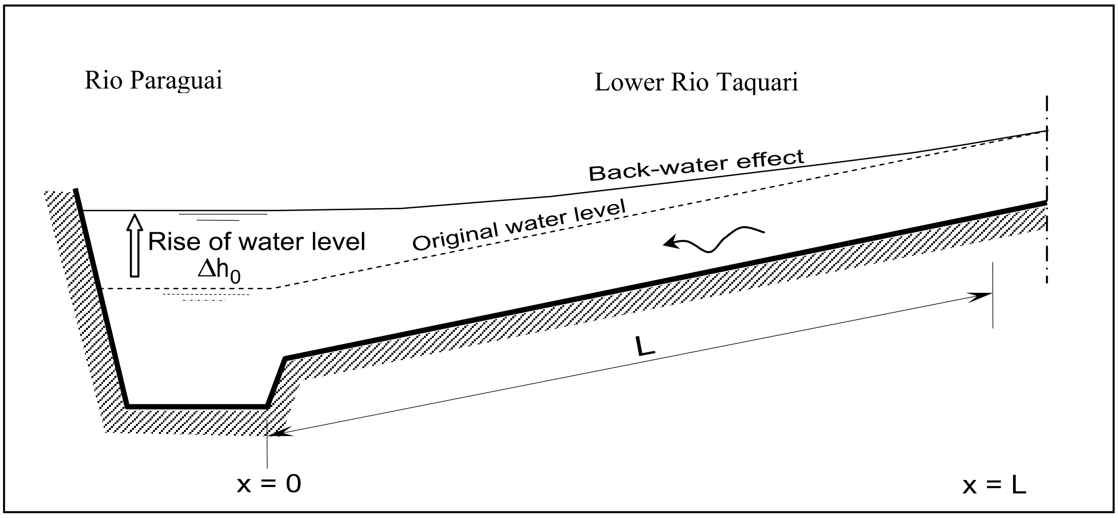

Figure 5.11 Example of the back-water-effect

A rise of the water level at location X = 0km will be noticed upstream in the Rio Taquari over a certain distance X. The resulting increases in water level along the river can be estimated with the Bélanger equation:

$$\frac{dh}{dx} = i_b \left[\frac{h^3 - h_n^3}{h^3 - h_c^3} \right] \tag{5.6}$$

The Bélanger equation arises when the momentum equation and the continuity equation for one-dimensional steady flow per unit of width is rewritten, utilizing expressions for the equilibrium water depth (h_n) and the critical water depth (h_c).

The equilibrium or normal water depth h_n (m) is the water depth in a steady situation according to Chézy and is calculated with:

$$h_n = \left(\frac{q^2}{C^2 i_b} \right)^{1/3} \tag{5.7}$$

with q (m^2/s) as the width-averaged discharge:

$$q = \frac{Q}{B} \tag{5.8}$$

The critical depth of flow h_c (m) is defined as the water depth at which the Froude number equals 1, in which case the flow transfers from sub-critical (tranquil) flow to super-critical (shooting or rapid) flow. It can be calculated with the following relation:

$$h_c = Fr^{2/3} h_n = \left(\frac{q^2}{g} \right)^{1/3} \tag{5.9}$$

with:

$$Fr = \frac{u}{\sqrt{g h_n}} \tag{5.10}$$

Simplifications of the Bélanger equation are available but are generally not valid for larger differences in downstream water level or higher Froude numbers. Therefore, the actual

Bélanger equation was solved numerically, using a simple explicit scheme with a predictor corrector method and using the following characteristic values of the Rio Taquari:

Discharge Q	=	200m^3/s
River width B	=	50m
Chézy-roughness C	=	50 – 70m$^{1/2}$/s
Variable longitudinal bed slope i_b	=	0.011 – 0.229 m/km

The bed roughness C has been approximated with the relation between the flow velocity u, the water depth h and the water level slope i, according to Chézy:

$$u = C\sqrt{hi} \tag{5.11}$$

This has been examined using the Nikuradse sand roughness and White-Colebrook formula. In the absence of bed forms, the Nikuradse roughness k_s is correlated with the sediment grain size, and can be approximated by:

$$k_s = 2.5 \cdot D_{90} = 2.5 \cdot \left(2 \cdot D_{50}\right) \tag{5.12}$$

Subsequently, the Chézy roughness can be calculated with the White-Colebrook equation:

$$C = 18 \cdot \log\left(\frac{12 \cdot R}{k_s}\right) \tag{5.13}$$

with R (m) as the cross-sectional hydraulic radius, which almost equals the water depth for large width-depth (B/h) ratios:

$$R = \frac{A}{P} = \frac{Bh}{2h + B} \tag{5.14}$$

The parallel report on the river survey showed that the D50 of the river bed sediment varies between 0.13 mm and 0.26 mm. The river bed of the Rio Taquari has been found to be smooth during the field mission. Both flow characteristics and sediment characteristics lead to the conclusion that the Chézy-roughness C will be on the order of 50 – 70m$^{1/2}$/s.

The water level is characterized by a mild slope near the Rio Paraguai and gradually steepening in upstream direction. For the determination of the back-water curve this was taken into account by assuming that the bed slope equals the water level slope, which was measured during the River Survey (see the parallel report). The numerical solution of the Bélanger equation for the Rio Taquari has been plotted in Figure 5.12. This figure shows the bed level profile used and the calculated water levels up to a distance of 140km upstream of the confluence point. The net longitudinal water level rise for several water level rises in the Rio Paraguai, compared to the fully steady situation without a downstream rise in water level, has been plotted in Figure 5.13.

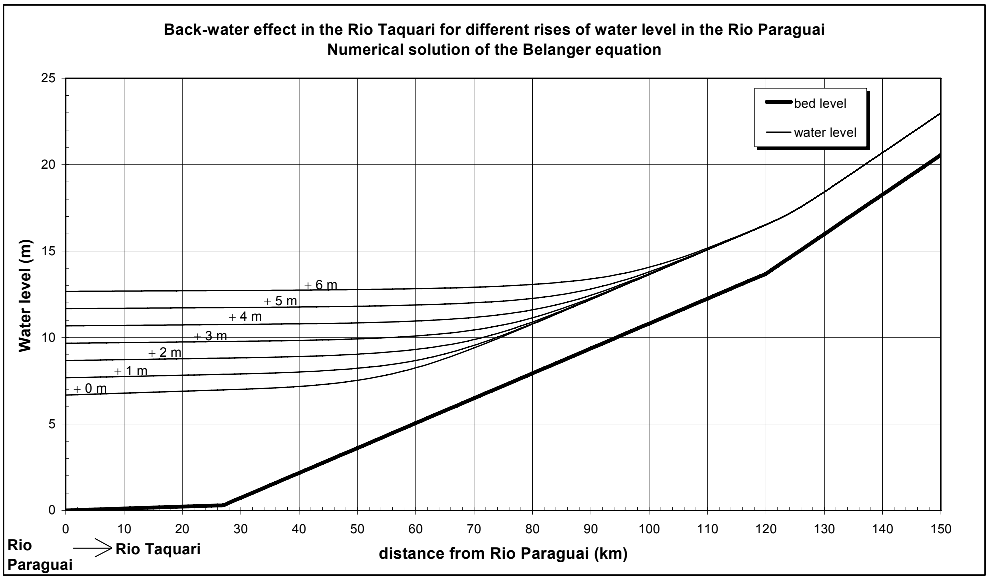

Figure 5.12 Backwater effect in the lower Taquari based on the transition in longitudinal bed slope

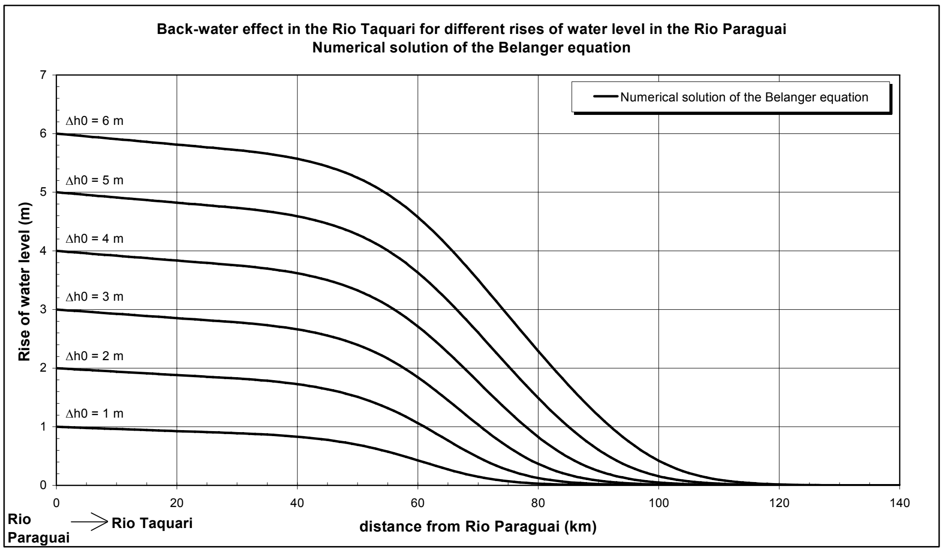

Figure 5.13 The actual rise of water level in the lower Taquari due to water level rises in the Rio Paraguai

From the figures above the following conclusions can be drawn:

- The larger the downstream water level rise, the further upstream it will be still noticeable.
- Sixty km upstream of the confluence still a considerable (50 – 70%) effect of the downstream rise will be felt.
- At an upstream distance of 80km the downstream water level rise of 1 m will hardly be noticed anymore (downstream of Zé da Costa). For a downstream water level rise of 6 m, this location lies further upstream at a distance of approximately 110km (Porto Rolon).

An important source of sensitivity of this approach lies in the hydraulic parameters used. Therefore, it is worth noting that the following adaptation of the parameters will lead to enlargement of the upstream distance of influence:

- An increased discharge;
- An increased roughness (or a lower Chézy-value);
- A smaller river width; or
- A less steep bed slope.

Remark that for higher water level rises in the Rio Paraguai and for higher discharges in the Rio Taquari, the river width in certain sections of the Taquari increases considerably, as floodplains will inundate. In those cases the distance of influence will hardly increase.

From this exercise it can be concluded that it is possible that a part of the flooding problems in the lower Taquari is caused by the rise of water levels in the Rio Paraguai. This conclusion can be further verified with numerical calculations. It is worth noting that backwater effects produce sedimentation and enhanced braiding in the downstream reach (not along the whole river and not related to sediment overloading upstream).

Effect of distance to the Rio Paraguai

The fourth hypothesis is that the distance to the Rio Paraguai has become longer. Channel migration of the Rio Paraguai or the downstream reach of the Rio Taquari may increase the distance (along the river) between the area of the flooded farm land and the confluence. This leads to higher water levels on the Rio Taquari and its surrounding terrains.

The Rio Taquari can be divided in different longitudinal sections, based on several characteristics, like the ones being given by Souza et al. (2002): *i*) an upper meandering part, *ii*) an anastomosing part and *iii*) a lower delta part.

The river in these sections is continuously moving. The change of a straight river section to a meandering river involves an increase in river length. For an equilibrium situation it can be shown that this will cause larger water depths. The momentum equation for steady uniform flow reads:

$$Q = CBh^{3/2}i^{1/2} \tag{5.15}$$

The slope i is defined by:

$$i = \frac{\Delta z}{L} \tag{5.16}$$

in which L equals the length of a river reach and Δz equals the drop in water level over that reach. If we assume that the river discharge, Q, the width, B, the bed roughness, C, and the drop in water level, Δz, are uniform along the river we find a relation between the water depth and the bed slope:

$$\left(\frac{h_2}{h_1}\right)^{3/2} = \left(\frac{i_1}{i_2}\right)^{1/2} = \left(\frac{L_2}{L_1}\right)^{1/2} \tag{5.17}$$

with index 1 as the initial condition and index 2 as the condition of the elongated river.

These relations teach us that an increase in river length causes a decrease in slope and an increase in water depth.

It is also worth noting that an increased length of the downstream reach produces sedimentation and enhanced braiding in that reach (not along the whole river and not related to sediment overloading upstream).

The meandering character of the Lower Taquari over long distances can be inferred from Figure 5.14, which shows the sailed path during the field survey (blue lines). The right arrow shows a detail of the Caronal avulsion location, with the purple line as the upper part of the New Caronal river stretch. The left arrow in Figure 5.14 shows the downstream section of the Lower Taquari. Here, the blue line represents the sailed path during the last field trip and the red line is the path that was sailed several years ago, which rather differs from the first. Because this Lower Taquari area is meandering and anabranched, it is possible that both lines represent current active channels of the Lower Taquari.

A change in sinuosity of the Rio Taquari can indicate a change in river length, which might be one of the explanations of higher water levels. No major changes in sinuosity, however, are observed in the sailed path as well as on satellite images of different years. Only the (outer) bank deterioration in the upper part of the Lower Taquari might suggest such a development. On the basis of this information, the sinuosity is concluded to have remained constant.

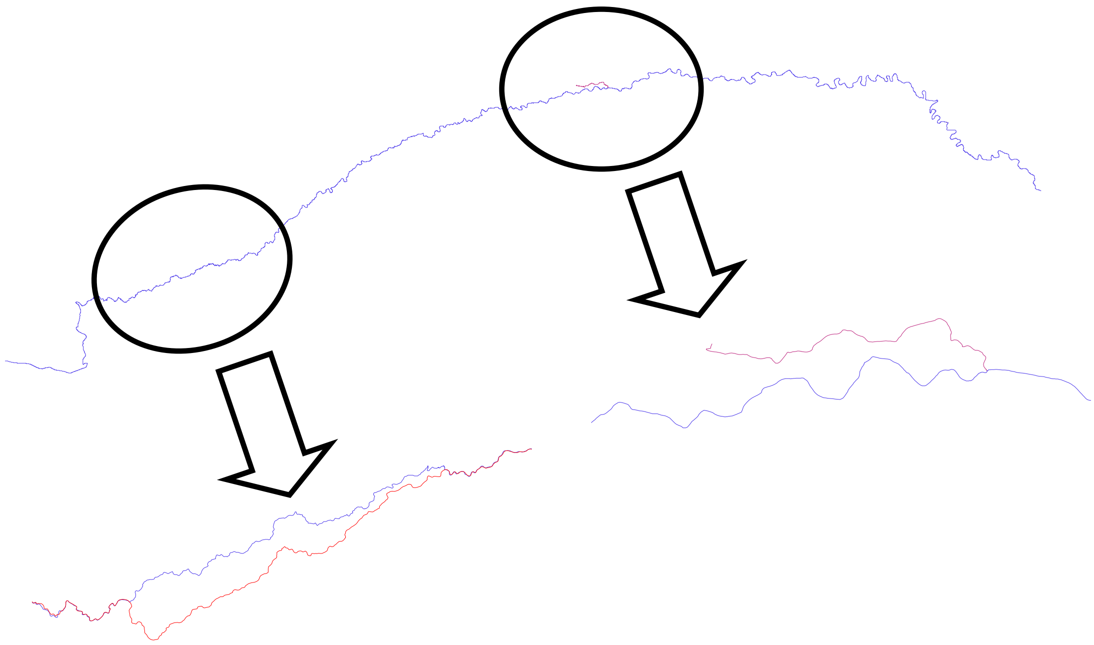

Figure 5.14 Sailed path along the Rio Taquari during the last field trip

Possibly the abandonment of the Taquari Velho in favour of the Rio Negrinho - Paraguai Mirin at the Arrombado Zé da Costa has led to larger distances to the Rio Paraguai (the Rio Negrinho and the Paraguai Mirin became active in 1988). In 1996, they already conveyed 70% of the discharge of the Rio Taquari (information Sergio Galdino of Embrapa Pantanal). An inspection of satellite images shows that this distance has not increased. Another possible cause of an increased distance to the Rio Paraguai would be that the Paraguai has moved east. However, the satellite images do not show any signs that this has taken place. Furthermore, it is also not the case that the new Caronal is longer than the old Lower Taquari.

Effect of overland flows from elsewhere
Several drainage directions can be identified on the alluvial fan of the Rio Taquari. Recent satellite images suggest that the course of the Rio Taquari is no longer the dominant drainage direction during floods. It might be that the farm land under consideration is actually flooded by water that leaves the river somewhere upstream (Arrombado Caronal, since 1999) and reaches the farms by overland flow. If the drainage is slowed down or blocked by the local topography, the water levels on the farm land may become higher than the water levels in the river. This leads to the fifth hypothesis that the farm land is flooded by overland flow from elsewhere.

During the field mission it was observed that the New Caronal is becoming the dominant branch of the Taquari at the cost of the old lower Taquari. This is even more the case, as also the old Caronal avulsion leads discharge from the Taquari to the same Caronal branch. This morphological development is expected to continue.

Furthermore, water levels in the lower Taquari and the upstream part of the Caronal were slightly lower or equalled the level of the surrounding terrain, although there were no high water levels during the field mission period. A new flood will immediately inundate al the surrounding land. Satellite images confirm that the areas along the Caronal are becoming more prone to flooding, whereas areas along the old lower Taquari are becoming less prone.

Effect of an extreme flood around 1974
Perhaps river bank erosion during an extreme flood around 1974 (possibly related to the simultaneous arrival of flood peaks on the Rio Taquari and the Rio Paraguai) has widened the river. The result of this widening may be local sedimentation (not related to sediment overloading from upstream) and possibly braiding. The natural recovery from this widening is very slow, possibly requiring decades. Therefore, the sixth hypothesis reads: The river has become wider and more braided due to an extreme flood around 1974.

If a flood would have widened the Rio Taquari, the first effect would be a general lowering of the water levels. Subsequently, the river would adapt to its new width by means of a morphological change. Two stages are examined in the morphological adaptation process:
1 An initial adaptation, which is the dynamic change of the river immediately after the widening;
2 A final equilibrium situation, which is the "end" stage at which the river has been completely adapted to the new configuration.

Most of the measured cross-sections in this lower region, of which an earlier cross-section reference was available, show an increase of the main channel width of approximately 20m within the last 10 years. This confirms that widening has occurred. The immediate effect is a decrease in water levels, but also a localized sedimentation that gradually increases its extent over the river. Considering the time scales that arise from the computations in Section 2, it is expected that the sedimentation due to widening in 1974 will now be able to cause higher water levels only in limited reaches of the river.

The aggradation and the shallower river may have resulted in braiding. Such braiding is seen in the Rio Taquari between Zé da Costa and the Paraguai Mirin.

5.7 Conclusions and recommendations

Flooding and sedimentation along the Lower Taquari is a major issue, in particular for the farmers that are affected by these processes. This report has assessed the causes of the sedimentation and flooding problems by testing several hypotheses. The conclusions are summarized in the table 5.5.

Table 5.5 Summary of the findings regarding the causes of the sedimentation and flooding problems along the Taquari.

Hypothesis	**Findings**	**Plausibility**
Sedimentation due to sediment overloading upstream (Planalto)	Small sediment yield from the Planalto despite changes in land use. The Planalto produces mainly washload that does not cause aggradation of the river bed. Sediments in the Lower Taquari stem mainly from bank erosion within the Pantanal. Local sediment overloading at Caronal bifurcation leads to sedimentation in old Lower Taquari, not in new Caronal. No indications of sedimentation in river planforms on satellite images. Higher sediments inputs from the Planalto over the last 30 years would only have caused sedimentation in the upper 150km of the Lower Taquari (downstream Coxim).	NO
Higher discharges in recent years	Higher discharges are inferred from higher water levels at all gauge stations. No reliable information is available on changes in precipitation.	YES may account for decimetres up to a few metres higher water levels

Hypothesis	Findings	Plausibility
Higher water levels on the Rio Paraguai	Water levels on the Paraguai have risen by 1 to 6 m since 1974. A 1 m higher water level on the Paraguai increases the water level 60km upstream along the Taquari by 0.4 m. A 6 m higher water level on the Paraguai increases the water level 80km upstream along the Taquari by 2.3 m. A higher water level on the Paraguai can cause sedimentation in the lower reaches of the Taquari. Avulsion from the old Lower Taquari to the new Caronal implies that the Taquari debouches in a higher part of the Paraguai.	YES may account for decimetres up to a few metres higher water levels downstream of Porto Rolon as well as on a large part of the Caronal
Longer distance to Paraguai	No signs of change in sinuosity. No signs of eastward or westward movement of the Rio Paraguai.	NO
Overland flow from elsewhere	During the field mission it was observed that the Caronal is becoming the dominant branch of the Taquari, at the cost of the old Lower Taquari. Satellite images confirm that the areas along the Caronal are becoming more prone to flooding, whereas areas along the old Lower Taquari are becoming less prone.	YES (effect on water levels not quantified)
Widening and increased braiding	Cross-sections recorded during the field mission show that, within the last 10 years, the river widened by about 20m between Ze da Costa and the Paraguai Mirin. This reach is also braided.	YES may locally account for higher water levels, despite the overall effect of lower water levels

The flooding and sedimentation problems can thus be explained from a combination of higher discharges of the Taquari, higher water levels on the Paraguai, river widening and a developing avulsion at Caronal. An important finding is that the problems cannot be ascribed to changes in land use on the Planalto. As a consequence, a dam at Coxim would not be an effective solution.

Considering the possible causes of the flooding and sedimentation problems, only mitigating measures that affect the process of avulsions and associated channel evolution seem feasible. For this, it is recommended to study the processes at the bifurcations in more detail.

Management options to modify the development of avulsions include dredging and the application of recurrent measures of local materials. It is worth noting that these measures are currently applied, albeit illegally: some farmers dredge the river bed, dig cut-off channels and counteract avulsions by means of sand bags and brushwood, whereas some fishermen create breaches that may develop into avulsions. The latter produces conflicts between fishermen and farmers. All interventions produce conflicts with nature conservationists. A proposed point of discussion for a management and decision support system is the legislation regarding dredging and corrections of local avulsions. The current total ban may be too strict for this type of local small-scale interventions. Allowing these interventions locally may be a management instrument. However, less strict legislation may require stronger control of compliance and stronger sanctions of violations. Finally, it is recommended to assess the possibilities of additional non-technical solutions, such as:

1 indemnifying or buying out farmers,
2 system of sharing land for cattle grazing.

6 Groundwater modelling

Remco Jonke[12]r and Erik Querner[13]

6.1 Introduction

In recent decades the frequency of flooding in the Lower Taquari (Mato Grosso do Sul, Brazil) has increased considerably, causing harm to ecology and farmers. Although the alluvial fan of the lower Taquari has always been characterized by the presence of wetlands (Pantanal) and the distributary river system, the morphodynamic activity has become obviously higher. Causes of the problem have in the first place been attributed to the sanding up of the rivers. Besides the sediment load, water flow from the High Taquari to the lower areas also increased. The rise of the problems of sediment deposition and inundations went simultaneously with the colonization of the High Taquari, leading to cultivation of the land, as well as an overall increase of precipitation. However, uncertainty exists about the extent of the impact of these possible causes on the hydrologic system of the Taquari River basin. This study has been carried out to clarify the effects of these factors.

A hydrological model has been built, comprising the High Taquari, the whole lower alluvial fan and the area in between. This is done by means of Simgro, an all-in hydrological model that is able to simulate surface water flow as well as the flow in the saturated zone and the unsaturated zone. Data and information has been collected about ground elevation, geohydrology (hydraulic conductivity, presence of layers and their thicknesses), presence of rivers and their hydraulic properties, drainage channels, soil types and land use. On the other hand time-dependent data has been collected to be able to calibrate and validate the model, create scenarios and define boundary conditions. This data consists of measured discharges, rainfall and evaporation.

The model area has been schematized into 9.116 nodes to which spatially varying properties are attributed. The surface water system has been modelled as subcatchments that all got assigned their own stage-discharge relationship that has been derived from the hydraulic properties. There are 238 subcatchments in total.

Calibration of the model has been carried out on the basis of measured discharges. Stage-discharge relationships were improved to create a better match between the runoff from the highlands with the measurements. In the lower Taquari (Pantanal) the improvement was reached by changing discharge distributions at avulsion points. Validation showed that the model was able to cope with different circumstances.

To get an answer on the initial questions, calculations have been carried out with different scenarios that varied on total rainfall and the presence of cultivated land use. The results showed that the increase of rainfall resulted in an even higher increase of discharges along the rivers and area of inundations. The presence of cultivated land use on the other hand showed hardly any effects.

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Although, the lack of data has resulted in a doubtful schematization, the results are so clear that they can be taken for granted. It is above all the physical base of the model that makes it possible to make use the model in future for different purposes such as the prediction of effects of measures. Although, it must be taken in account, that for certain aspects, especially the prediction of inundations, the model still might show features of unreliability.

6.2 Hydrological data

In hydrology it is common to create a model at the level of a catchment or a subcatchment. In this project the model area is larger than the catchment (Figure 4.1). The reason is that there is no hard definition of the Taquari River basin. In the lower Taquari (the fan region) there are many avulsions and old river channels. The river system is a maze of channels. Also the lack of knowledge about groundwater urged to expand the model area. Although the Taquari catchment is assumed to be very narrow at the intersection between the BAT and the Pantanal it is not for sure that groundwater is bounded to the borders of the surface water system.

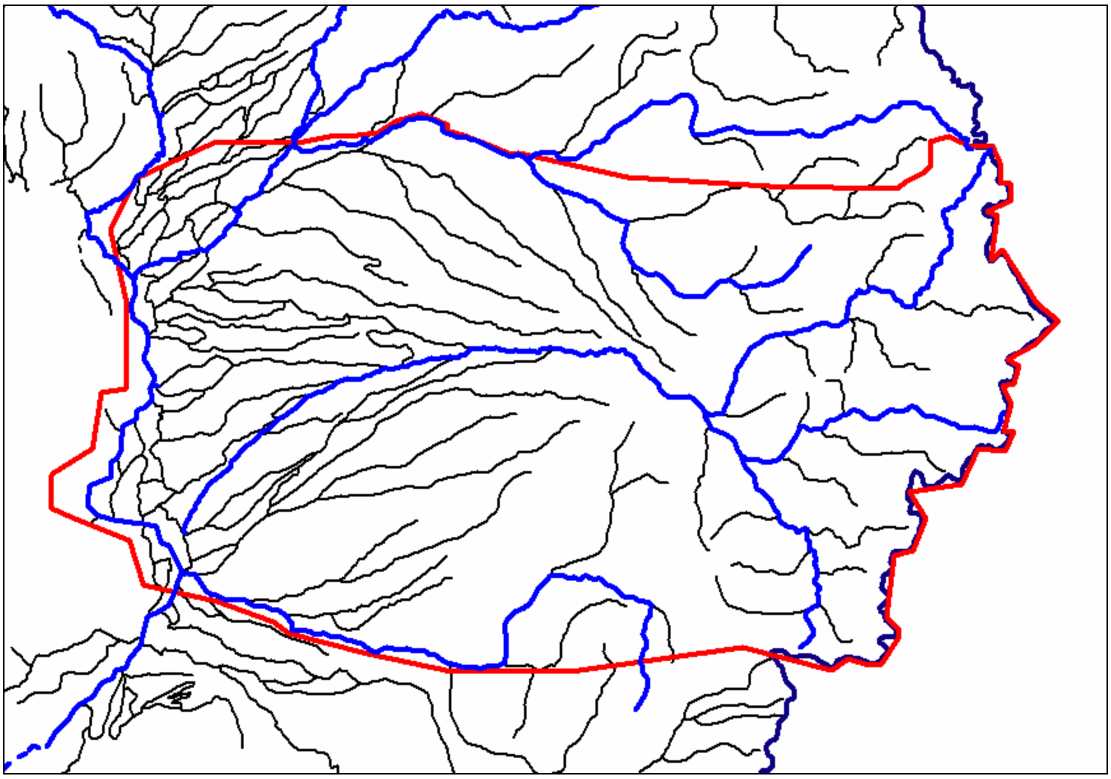

Figure 6.1 The model area

Geohydrological knowledge such as hydraulic conductivity, presence of aquifers and aquitards, thicknesses of layers is very scarce. The PCBAP study contained some information about measurements of k-values. These measurements have been carried out in a laboratory with samples that have been taken at a depth of 4 m. The values of the samples that were taken at locations in or close to the model area are shown in Figure 6.2.

Besides the samples, PCBAP also contains information about wells from which geohydrologic properties of the soil could be derived. The information comprises:
- location of a well
- radius of the well
- water level without any withdrawal of water
- water level with a constant withdrawal of a certain quantity of water
- the accessory certain quantity of water

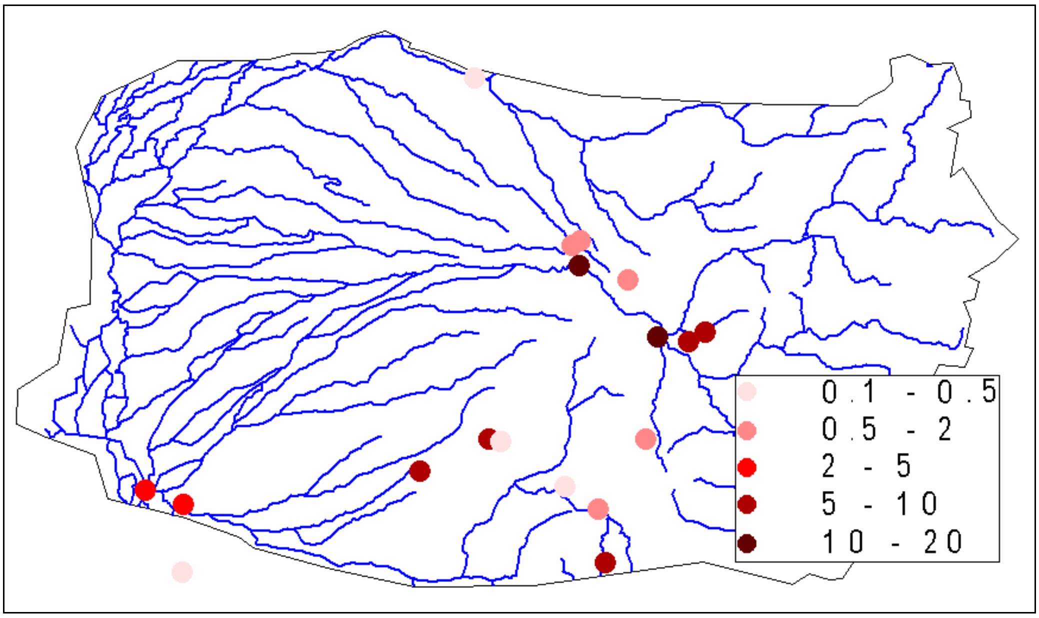

Figure 6.2 Measurements of k-values (k-values in m/d)

A hydrological study, carried out by Unesco from 1966 till 1972, is the sole provider of information about stratification of soils (Unesco, 1973). According to this report, three main formations are present in the model area:
- Chapada Series
- Aquidauana Series
- Quaternary Deposits (Pantanal Formation)

The Chapada and Aquidauana series are present at the Planalto and mainly consist of consolidated rock, while the Pantanal is formed out of fluvial deposits. Information about the Pantanal formation origins from measurements by Petrobrás from the 1960s.

Series of groundwater measurements could have been very useful in this project for the determination of the initial state or for calibration and validation of the model. Unfortunately, hardly any measurements are available. Little information is given by in PCBAP or the UNESCO study, but these are just a few, coarse, measurements with only a meaning at a very local scale.

Next to the description of the geohydrology, soil types have to be defined for the model area. This description corresponds to the composition of the top soil layer, where plant - atmosphere interaction takes place. The PCBAP database contains a soil map with a very high level of detail. By means of a Brazilian soil type classification 115 soil types have been indicated in the project area. The soil classification has been adapted on hydrological properties (Figure 6.3).

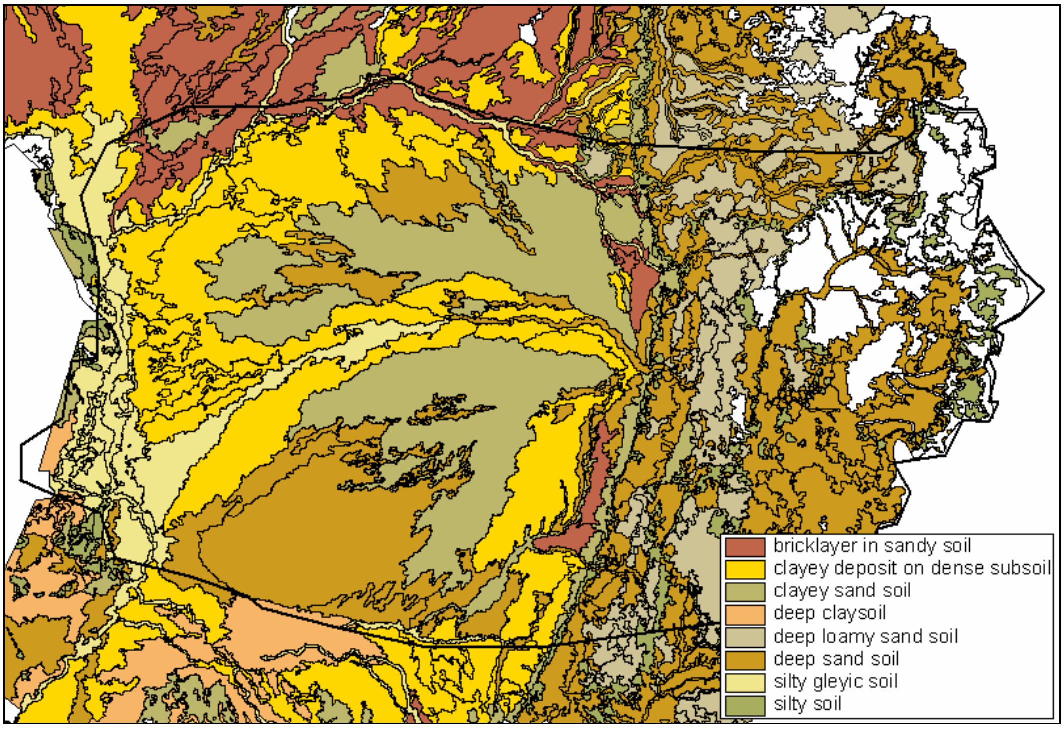

Figure 6.3 Soil map

The retrieval and processing of land use data, has gone more or less the same as the soil data. PCBAP distinguishes 27 vegetation types in the model area that can be divided in 9 main classes. The classification scheme is Brazilian standard. Figure 6.4 shows the presence of vegetation in the model area classified by the main categories. Figure 2.16 shows the development of cultivated land use for the years 1976, 1984 and 1991.

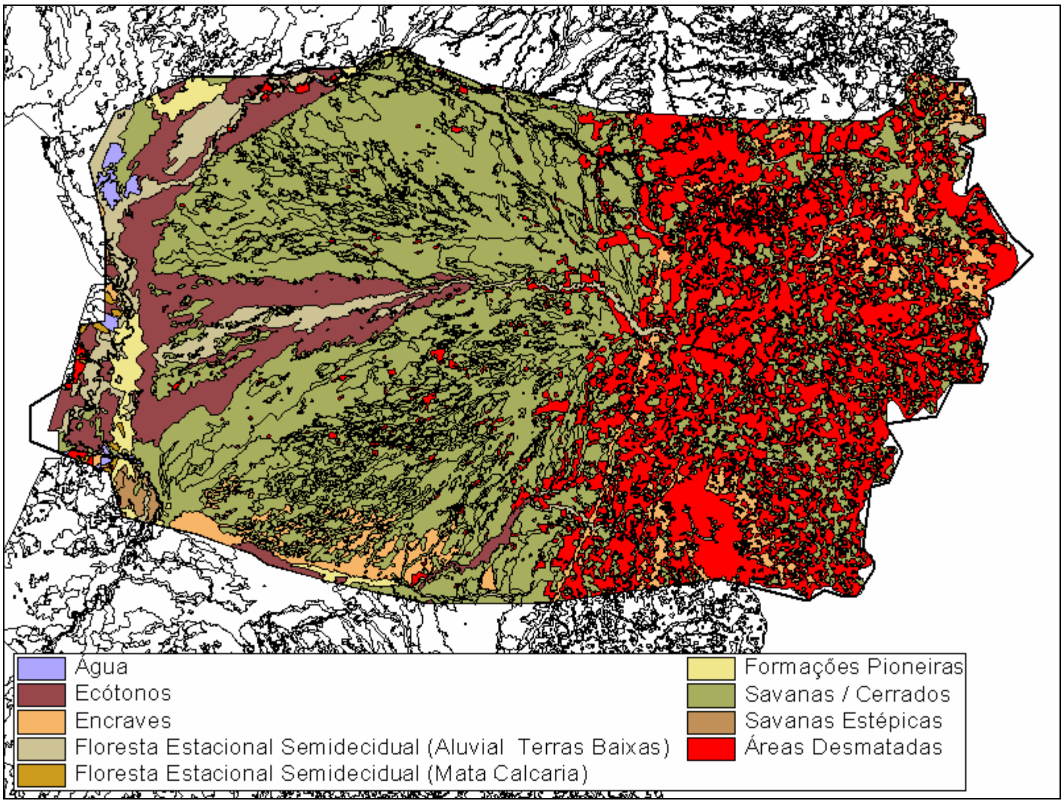

Figure 6.4 Vegetation according to PCBAP (1991 situation)

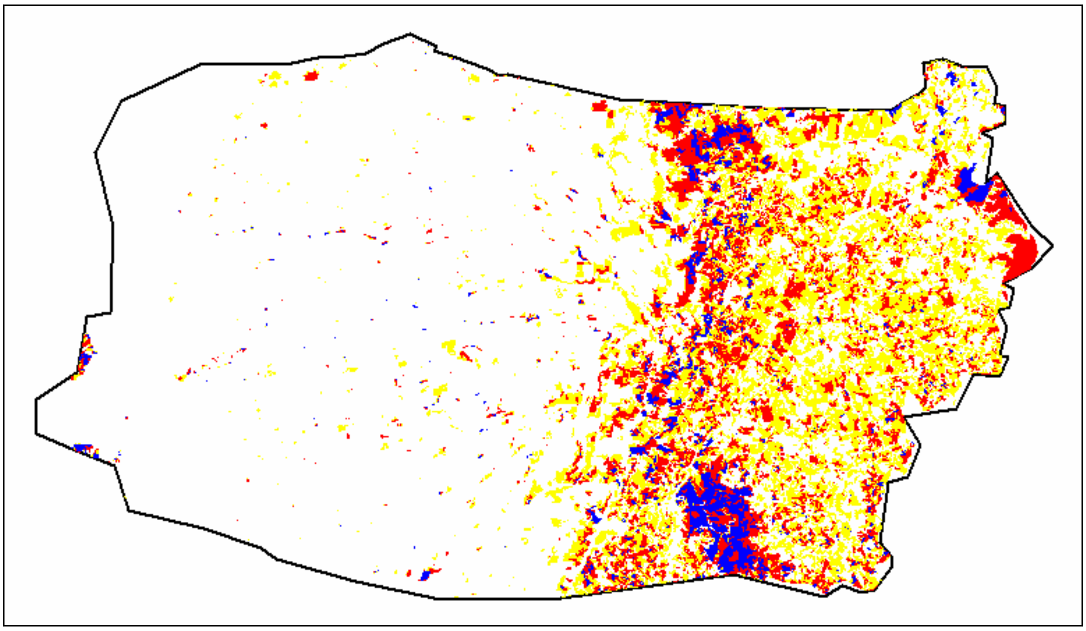

Figure 6.5 Cultivated land in 1976 (blue), 1984 (red) en 1991 (yellow)

6.3 Hydrological modelling

The model SIMGRO (SIMulation of GROundwater flow and surface water levels) simulates regional groundwater flow in relation to drainage, water supply, sprinkling, subsurface irrigation and water level control. The model simulates the flow of water in the saturated zone, the unsaturated zone and the surface water in an integrated way. The model is physically-based so it can be suitable to be used in situations with changing hydrological conditions. Figure 6.6 shows a picture of the processes that are included in Simgro.

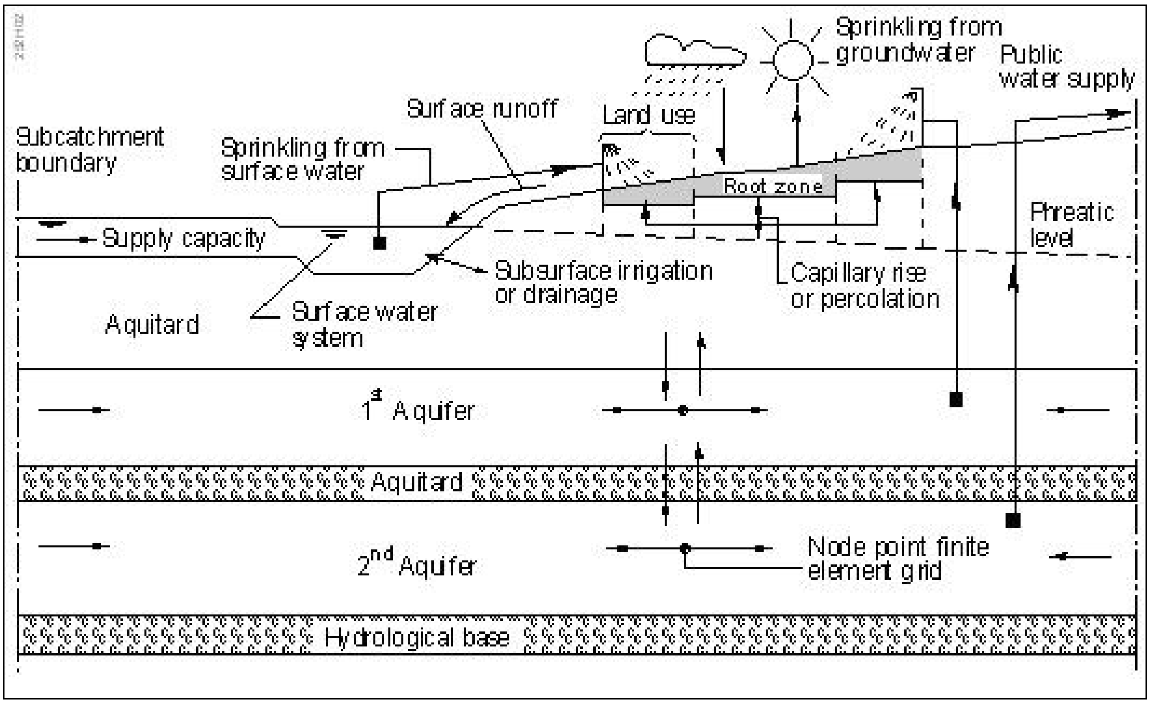

Figure 6.6 Scheme overview of the Simgro model

The modelling domain has to be schematized geographically, both in the horizontal as well as in the vertical direction. In the horizontal direction the groundwater system is schematized as a network of nodes. The soilwater system uses nodal subdomains (polygons around nodes) for its calculations. The surface water system is schematized as a number of catchments, which are formed by a network of subcatchments. Each subcatchment is modelled as one surface water reservoir. In the vertical direction the groundwater system is subdivided into a number of geohydrological layers (aquifers and aquitards). The soil water system consists of a root zone reservoir and a subsoil reservoir.

The groundwater module uses the quasi three-dimensional approach in groundwater modelling. Therefore aquifers and aquitards are to be specified. Horizontal groundwater flow can only take place in aquifers and is modelled using the finite element technique. The equation of motion for groundwater flow can be obtained by considering an aquifer and applying the principle of linear resistance (Darcy's law) and conservation of mass. The equation describing flow in an aquifer is:

$$\frac{\partial}{\partial x}\left(T_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y\frac{\partial h}{\partial y}\right)=A_e\mu\frac{\Delta h}{\Delta t_g}+Q_t \qquad 6.2$$

in which h is the hydraulic head (m), T the transmissivity (m^2/d), x, y the coordinates of the 2-D horizontal coordinate system (m); A_e the area (m^2); μ the storage coefficient (-); Q_t constant fluxes such as drainage, q_w, capillary rise, q_c and groundwater abstraction for water supply or sprinkling (m^3/d); Δh the change in hydraulic head during a time step (m) and Δt_g the time step of groundwater model (d)

In case of a confined aquifer the transmissivity can be defined as:

$$T = kD \qquad 6.3$$

with k as hydraulic conductivity (also known as k-value) and D layer thickness.

If the aquifer is a phreatic one, the transmissivity does not depend on the layer thickness but on the thickness of the water column (phreatic surface to bottom of layer).

The unsaturated zone is modelled as vertically oriented, 1-D models or 'columns'. Each type of land use, within any nodal subdomain, is modelled separately. The 1-D column model consists of two reservoirs, one for the root zone and one for the subsoil. If the equilibrium moisture storage for the root zone is exceeded, excess water will percolate to the saturated zone. If the moisture storage is less than the equilibrium moisture storage, upward flow from the saturated zone is simulated through capillary rise. The height of the phreatic surface is calculated from the water balance of the subsoil, using a storage coefficient which is dependent on the depth of the groundwater table. Special processes are included in the unsaturated zone model, such as surface runoff and hysteresis.

Evapotranspiration is determined by the crop and the moisture content in the root zone. For these calculations, recorded values of precipitation and potential evapotranspiration of a reference crop must be available. The potential evapotranspiration for other crops or vegetation types are derived from the values for the reference crop, by means of a multiplication factor that is specified for each crop and day of the year (This does not count for pine-forest and deciduous forest, these have to be specified directly as well). Reduction of potential evaporation to actual evaporation is based on a relative evaporation factor:

$$E_a = \alpha_E \cdot E_r \qquad 6.4$$

with E_a actual evapotranspiration, α_E relative evapotranspiration factor and E_r the reference evapotranspiration.

A typical surface water system consists of a dense network of watercourses, yet it is impossible to explicitly account for all individual watercourses in Simgro. The major watercourses are modelled as a network (i.e. a cascade) of reservoirs. For each reservoir a stage-discharge relationship has to be defined in conformity with:

$$Q = c \cdot \left(\Delta h\right)^{n} \quad 6.5$$

with Q is the discharge (m^3/d); c is constant (m^{3-n}/d); Δh is differential head (m) and n a discharge factor (-)

The exchange between groundwater and surface water is calculated using a drainage resistance concept in conjunction with head differences between groundwater and surface water:

$$q_w = \frac{h_g - h_{sw}}{\alpha Y} \quad 6.6$$

in which q_w is drainage flux (m/d); h_g is the average groundwater level (m); h_{sw} is the surface water level (m), α is the geometry factor, depending on the shape of the groundwater table between drains, typically 0.65-0.85 and Y the drainage resistance (d). The drainage resistance itself depends on hydraulic conductivity of the soil and the density of the drainage network.

The dynamics of the movement of surface water through open watercourses evolve much faster than those of groundwater motion. Hence, the associated submodels have their own time step for numerical approximation. The result is that the surface water submodel performs several time steps during a single time step of the groundwater submodel. Groundwater levels are assumed to remain unchanged during any time step, whereas the interaction between groundwater and surface water is accumulated using the continuously updated surface water levels. At any call of the groundwater module, all water balance components associated with the unsaturated zone and the surface water submodels, like drainage- and sprinkler irrigation volumes, accumulated since the previous call, are used to update the groundwater level.

The model area is split the area into a certain amount of nodes. A huge number of nodes will be accurate, but not really practical in case of necessary calculation time. Hence, the total number of nodes should not be higher than 10.000. The network has been created by means of a small program called “Micro-FEM”. Since the discretisation of Simgro is based on the finite element method, nodes are not restricted to a certain grid and nodal domains can have different shapes. This gives the possibility to create a network of nodes with more or less the same mutual distances all over the model area, despite the capricious shape of the model boundary. The nodal distance that has been chosen is 3.500 m (that finally will be approximated by Micro-FEM), which corresponds with 9.116 nodes. Figure 6.7 shows the construction of the nodal network.

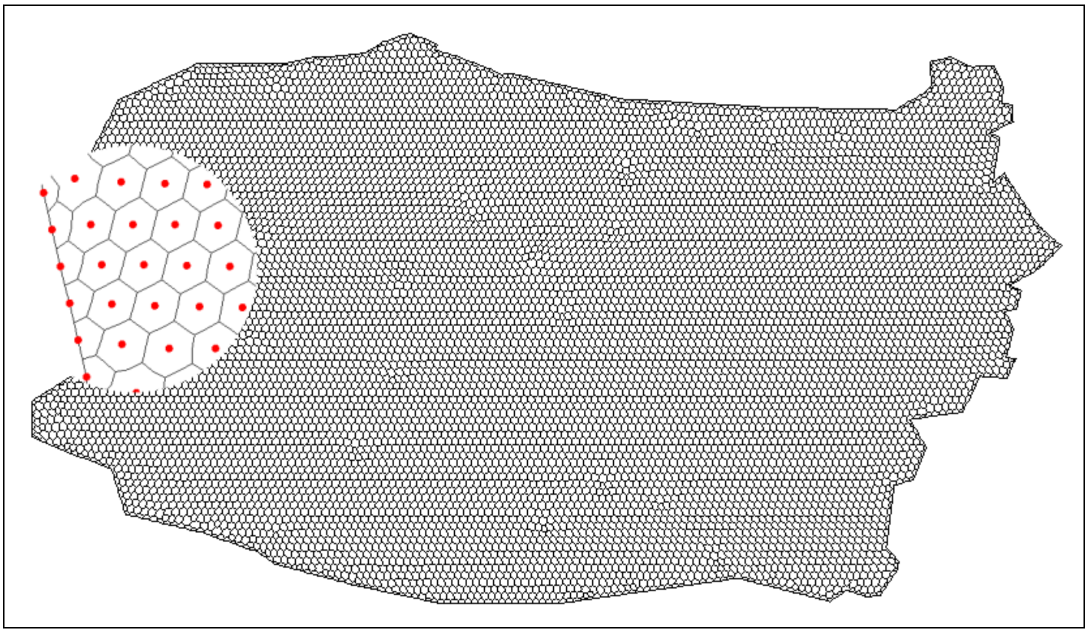

Figure 6.7 Partitioning of the model area in nodal domains

Elevations of the final DEM (Chapter 3) have been attributed to the nodal domains. Simgro uses the variance within a nodal domain to calculate the inundated fraction of it. A global analysis of the geology of the Pantanal has been made by Assine & Soares (2004) indicating a thick formation in the centre (around drill hole 6 and 7) of up to more than 500 m, decreasing rapidly towards the boundaries of the Pantanal. The soil stratifications in the drill holes are assumed to be representative for a certain area around them that is at the same depth scale as suggested by Assine & Soares (Figure 6.8). The Pantanal formation is split into three formations. Each formation itself is constant in properties (depth and hydraulic conductivity) over its area. Drill holes 4 and 5 as well as 6 and 7 will be merged and an average will be the representative situation.

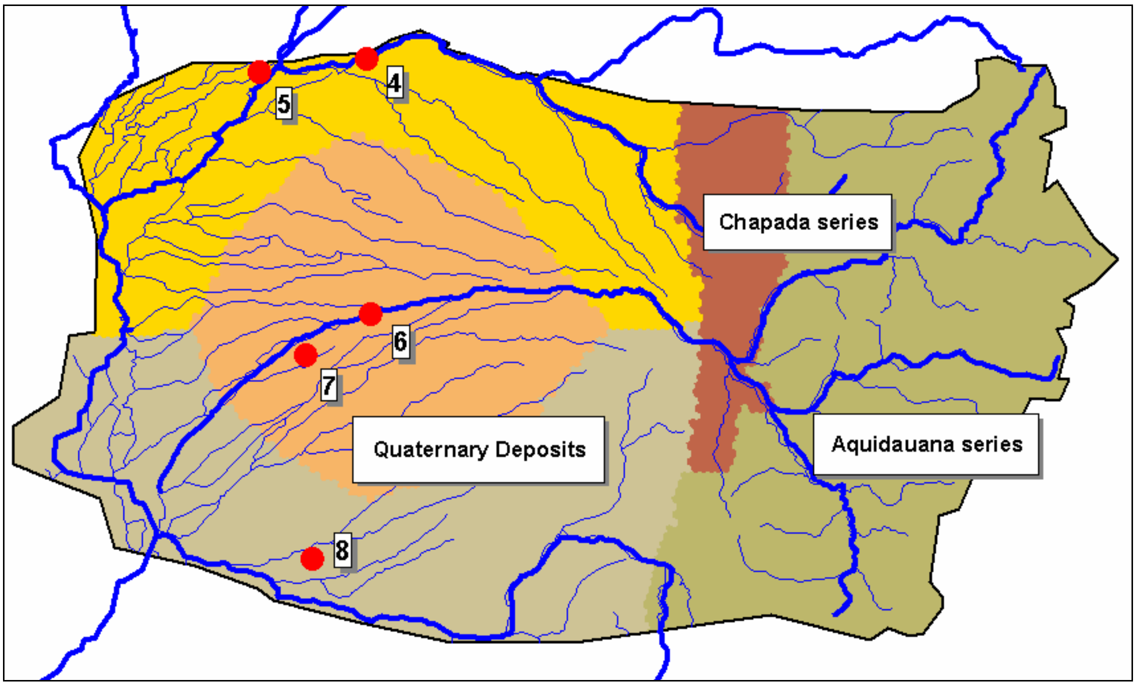

Figure 6.8 Partitioning of the Pantanal formation into three series.

In the pre-processing a map of river segments is needed to allocate and derive properties from. These properties are:
A list of river segments, in Simgro these are called subcatchments
A list telling which subcatchments are connected
Hydraulic properties of the subcatchments such as dimensions of the segments and slope to derive a stage - discharge relationship

Data that was available for the schematization of the dimensions of river segments (width, depth and slope of banks) only covered some segments of the big rivers. Dimensions of segments of main rivers have been derived directly from the available data (in case a cross-section at a location along a river segment was available) or by means of interpolation or extrapolation. Dimensions of smaller channels have been set to a default of 2/3 of the size of the smallest main channel segment (this "smallest" section is the last segment of Rio Coxim before it joins the Taquari River.

Now the hydraulic properties listed at the beginning of this paragraph have been attributed to the river segments, stage-discharge relationships can be calculated by means of AlterrAqua. For each river segment / subcatchment a certain (outflow) discharge is specified for a certain water level for every 10 cm. Note that bank or bottom roughness haven't been attributed to the river segments, despite the fact that AlterrAqua is able to work with user-specified coefficients. Data about roughness, however, is lacking, so AlterrAqua will work with default values.

AlterrAqua relates a stage-discharge of a certain subcatchment only to its own features. Features of downstream or upstream subcatchments are not involved, although Simgro is able to calculate backflow effects (this means that surface water outflow of a certain subcatchment depends on the water level of the downstream subcatchment). At bifurcations (when a river splits into two rivers) the default discharge distribution is 50-50. For Rio São Lourenço and Rio Paraguai the discharge distributions are based on assumptions. In this case the assumption is that in case of an avulsion (bifurcation) 90 % of the water will stay in the main channel. Measurements of discharge in Rio Taquari have indicated that the average discharge decreases from 426 m^3/s at Coxim to 199 m^3/s at Porto Rolon (Padovani et al., 1998(a)) (Places are shown in figure G.3). Between Coxim and Porto Rolon six avulsions have been included in the model. This would mean that an average of 12 % of the discharge flows out of the main river at each avulsion. This partitioning is used to correct the stage-discharge relationship of the lower Taquari.

For the definition of watersheds and subcatchments the DEM has been an important tool. By means of the "Hydrology – tools" of ArcView, watersheds can be determined. The total number of watersheds had to be more or less the same as the number of river segments in the map of watercourses (Figure 6.9). The total number of watersheds that have been clipped out of the original file with the model area is 276.

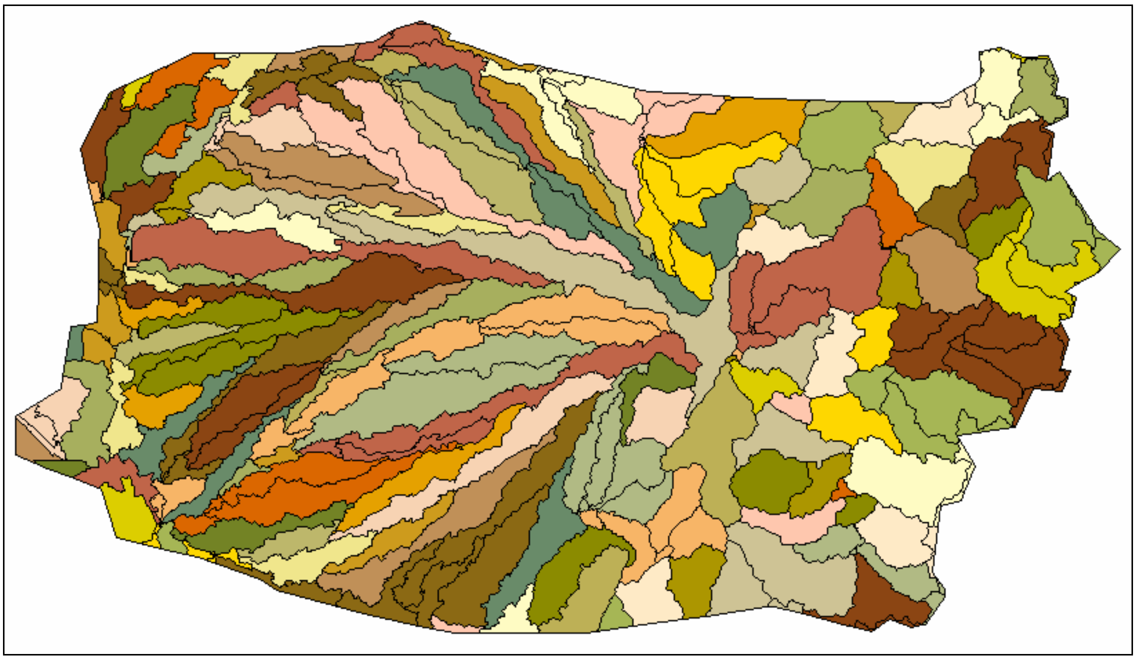

Figure 6.9 Watersheds determined by means of the DEM

With the map of the watersheds and the river segments, the assignment of nodes to subcatchments can be carried out automatically by means of AlterrAqua. The first result, however, was not satisfactory. This has been for some reasons.
In the first place the level of detail of the determination of the watersheds is not the same as the level of detail of the river system. Especially at local scale the variance is big. This is caused by the fact that the river system schematization has been created separately from the watershed determination.

Boundary conditions in Simgro apply to groundwater and surface water in- and outflow. Although boundary conditions are assumed to be time dependent, in the model they will be described with "hard" values. For this, there are two reasons. The first reason is the lack of data. Hardly any information is available about groundwater levels or flow at the boundaries. A little more is known about surface water levels and inflow, but not enough to be able to freely change the conditions in time without any problems. The second reason for the maintenance of steady boundary conditions is the research objective. To be able to relate the effects of precipitation and land use to its cause, the other conditions have to stay unchanged. The surface water conditions vary within a year, but not over the years.

A steady groundwater level of 1,5 m below ground level is assigned to boundary nodes with an altitude lower than 165 m above mean sea level. At these nodes net groundwater flow is assumed to take place, especially in the north – south direction. The higher boundary nodes are almost all at the Planalto. At the east side of the model boundary the boundary of the model follows the boundary of the watersheds, what means that no net flow will take place. At the north and south model boundary in the Planalto, groundwater is only assumed to flow in the east – west direction, so this line has been closed as well. The red nodes in Figure 6.10 have been assigned a constant groundwater level of 1,5 m below ground level and at the yellow nodes no groundwater flow trough the boundary takes place. Note that these assumptions were made after the first model runs.

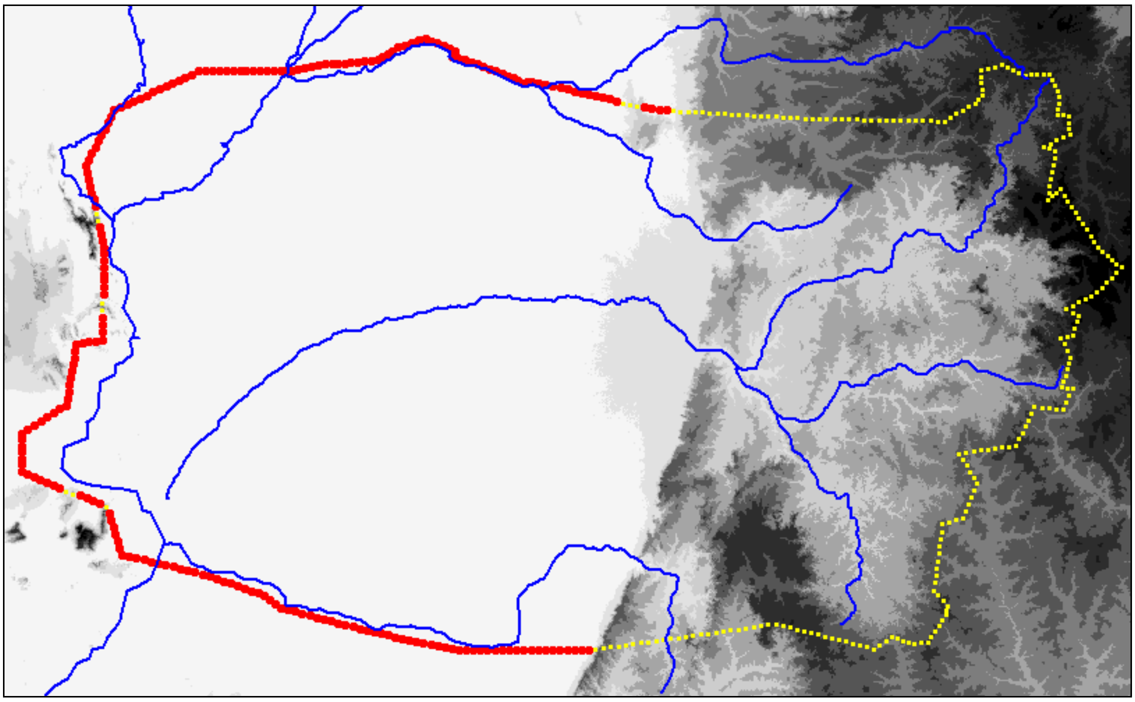

Figure 6.10 Groundwater level defined at boundary nodes

The boundary conditions of the surface water can be based on discharge measurements in the rivers around the model boundary. Surface water boundary conditions can be either described with a water- or weir level or with an inflow rate. The latter is used in this project. By means of discharge measurements at stations around the boundary, an inflow rate is defined for subcatchments that are likely to have a significant surface water inflow from outside the model area. The used measurement stations and subcatchments are shown on the map of Figure 6.11.

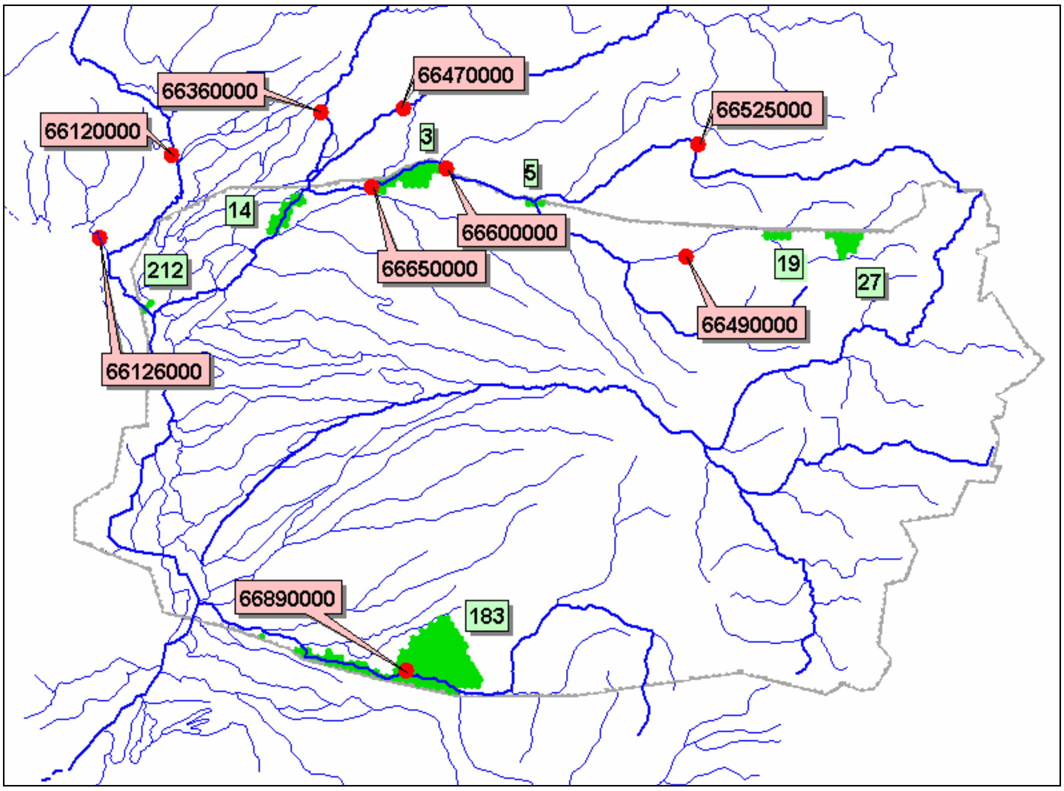

Figure 6.11 Discharge measurement stations that have been used to define inflow in subcatchments at the boundary

If the model, as described in chapter 3, is considered to represent the period of (roughly) 1960-1990, some time-dependent data are required to run the model. These data are:
- Precipitation
- Potential evapotranspiration
- Land use
- Initial conditions

Input of precipitation and potential evapotranspiration will be defined on a daily basis. During a model run land use can't change in time, but a representative setting has to be selected for each calculation period. Initial conditions will be estimated with model runs of which the final state will be a proper approximate state of the initial conditions of another run. From the set of available time-dependent data from 1960 to 1990, settings have to be created for:
- Adjustment, sensitivity analysis and calibration
- Validation
- Scenarios

Two main arguments are used for the selection of periods. In the first place there is the availability of data. This counts for input data, but in the case of calibration and validation, measured data also has to be available to be able to make a match with the output. Here, especially the presence of discharge measurements at the Taquari River is important. On the other hand each period has to represent a certain state of the hydrological regime. This means, for example, function as a wet period or a dry period (Table 6.1)

Table 6.1 Modelling periods

Model purpose	Period[14]	Land use setting
Calibration, etc.	1982-1983	1984 state
Validation	1985-1986	1984 state
Scenario dry	1970-1971	1974 state
Scenario wet	1987-1988	1991 state

The periods that are used all have a duration of two years. Because only complete rainfall and discharge series can be used within a calculation period longer periods have not been used. Especially for rainfall it is useful to work with several stations, so the regional variance of rainfall in the model area is involved in the schematization. The rainfall conditions in the modelling periods are shown in table 6.2.

Table 6.2 Rainfall in calculation periods

Model purpose	Period	Year	Average annual rainfall (mm)	Average of period (mm/year)
Calibration, etc.	1982-1983	1982	1.595	1.423
		1983	1.287	
Validation	1985-1986	1985	1.374	1.254
		1986	1.143	
Scenario dry	1970-1971	1970	1.061	1.131
		1971	1.201	
Scenario wet	1987-1988	1987	1.348	1.545
		1988	1.742	

Input data for calculation periods exists of meteorological data, land use and initial conditions. Simgro gives the possibility to work with different meteorological stations. By means of the Thiessen method, to each node the nearest station has been attributed. This process is carried out automatically with AlterrAqua that can work with stations situated up to 15 km out of the model area. In each period, as many rainfall measurement stations as possible have been used. This means: all stations with complete (2-year) measurement series in that period.

Because a station number has been assigned to each node, rainfall is defined at the daily base and the nodal scale. To improve the schematization of the spatial variance, two stations have been slightly moved to be involved in the process of attributing stations to nodes. Station number 1756000 has been moved approximately 9 km southward and station number 1753000 approximately 3 km westward.

Potential evapotranspiration can be defined at daily and nodal scale. However, potential evapotranspiration data is not available is such a variety as rainfall data. Local values of potential evapotranspiration have been calculated out of the measured data at the Nhumirim station (Table 6.3).

[14] These are hydrological years. So for example the year 1982 is actually the period from 1-10-1981 to 30-9-1982. From this point forward a year is considered to be a hydrological year.

Table 6.3 Values of annual potential evapotranspiration E_0 in the calculation period for Nhumirim

Period	Year	Annual potential evapotranspiration (mm)	Average annual potential evapotranspiration (mm)
1970-1971	1970	1680	1680
	1971	1680	
1982-1983	1982	1758	1741
	1983	1724	
1985-1986	1985	1583	1624
	1986	1664	
1987-1988	1987	1525	1546
	1988	1567	

After running a total period of several decades, groundwater levels had reached a more or less steady state. At nodes with an elevation higher than 220 m, what means more or less the Planalto, the average level of the phreatic surface is about 31,5 m below the ground level (at the start of a hydrological year, October 1) and hardly changes anymore (Figure 6.12).

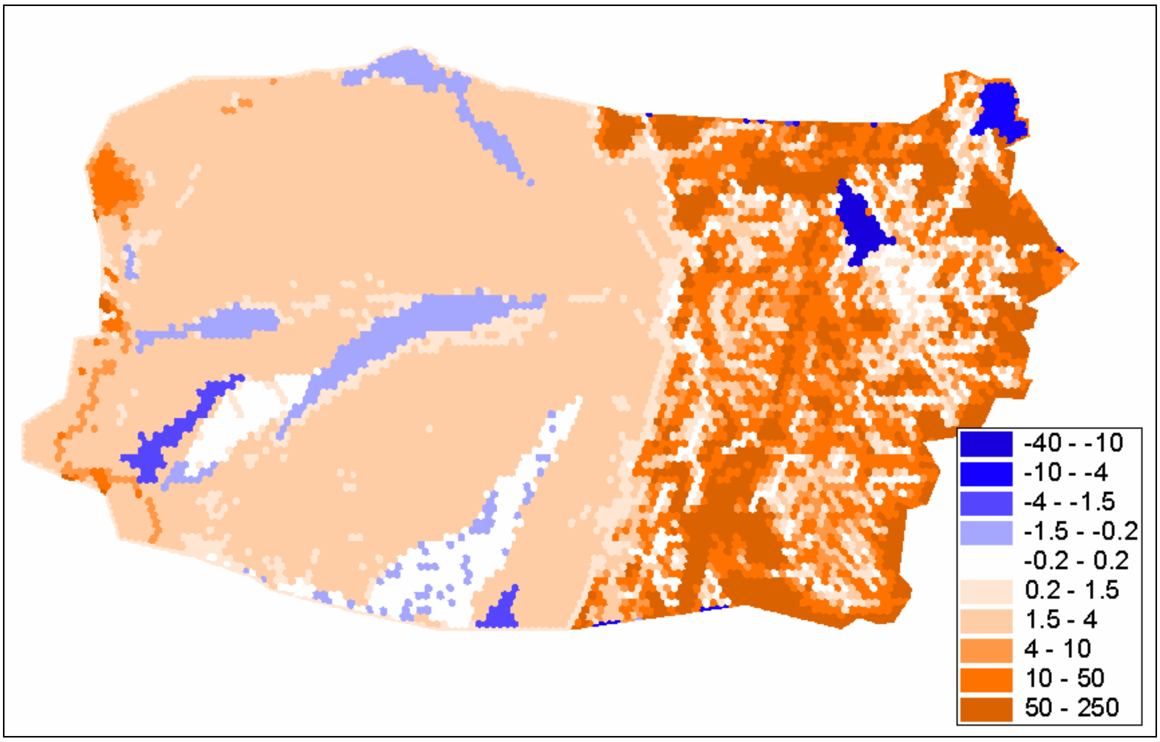

Figure 6.12 Initial groundwater levels (m below surface)

Figure 6.12 shows a very deep phreatic level in the mountains, which might be quite unrealistic. The only measurements endorsing the deep levels are the well measurements. They also show high values (deep water table). Four measurements are located in the part of the Planalto that is included in the model area. In these wells water levels have been found in the category of 6,5 m to 18 m below the surface. Given their location these values match with the map of figure 4.3. The measurements at the alluvial fan also show similarities with the groundwater map. At the twelve wells water levels have been observed of 1,6 m to 2,5 m below the surface, while at these locations the map of figure 6.12 give groundwater levels ranging from 1,47 m to 2,73 m below ground level. No well measurements are available at high places with very deep calculated phreatic levels, but just outside the model area water levels have been found of up to 100 m below the surface. However, considering the model as a whole, the groundwater levels in high areas are not of such a high importance. It is more important that these areas make a good simulation of their hydrological function.

A sensitivity analysis is carried out with input data prepared for the calibration, thus the period 1982-1983. A period of eight year will go prior to the calculations for the adjustment of the groundwater levels. As described in the previous paragraph, meteorological conditions in these eight years will be the average of the years 1982 and 1983. Before looking at the model output for the "real" calculation (of the period 1982-1983), the processes taking place in the first period will be pointed out.

Initially the effects of changing conditions are quite big, but when the groundwater levels adjust to the new state, the differences get smaller. The long period that goes prior to the actual calculation period is clearly not unnecessary. Just like the groundwater levels, the average trend, visible in the curve of the reference calculation, is a decreasing annual average discharge. Between 1975 and 1981 the average annual discharge calculated at Coxim decreases from 416 m^3/s to 403 m^3/s of which 5,5 m^3/s in the first year and 0,8 m^3/s in the last year. This means that the effects of the long term decrease of the groundwater levels are also visible in the discharges, but have reduced significantly in the adjustment period prior to the calculation. Besides, the effects of the meteorological changes in the years 1982 and 1983 are much larger than the background decrease of annual discharge. The average monthly discharge is reflected well in the model outcome (Table 6.5).

Table 6.5 Properties of calculated discharges at Coxim compared with the measurements

Calculation	Average relative monthly deviation from measurement	Average discharge 1982 (m^3/s)	Deviation from measurement	Average discharge 1983 (m^3/s)	Deviation from measurement	Average deviation of series (m^3/s)	Correlation Coefficient
SensRef	15%	522	18%	432	7%	168	0.964
Sens1	26%	573	30%	483	20%	150	0.960
Sens2	16%	472	7%	386	-5%	190	0.969
Sens3	14%	525	19%	431	7%	173	0.964
Sens4	15%	516	17%	432	7%	155	0.960
Sens5	17%	528	20%	446	11%	151	0.959
Sens6	12%	506	15%	418	4%	172	0.971
Measurement	0%	441	0%	404	0%	131	1.000

Validation is carried out to be able to estimate to what extent the model is able to resist changes. The validation is carried out in a different period, to deal with different meteorological circumstances. This period is the period 1985-1986, that has been attributed an average annual rainfall of 1.254 mm instead of the 1.423 mm used in the calibration period (Figure 6.13).

Especially at São Francisco the calculated discharge series starts too early with the rise and fall compared with the measurements. The conclusion can be made that annual discharges can be estimated even better with the model in (slightly) dryer years, but it also involves more unrealistic time shifts in seasonal variance.

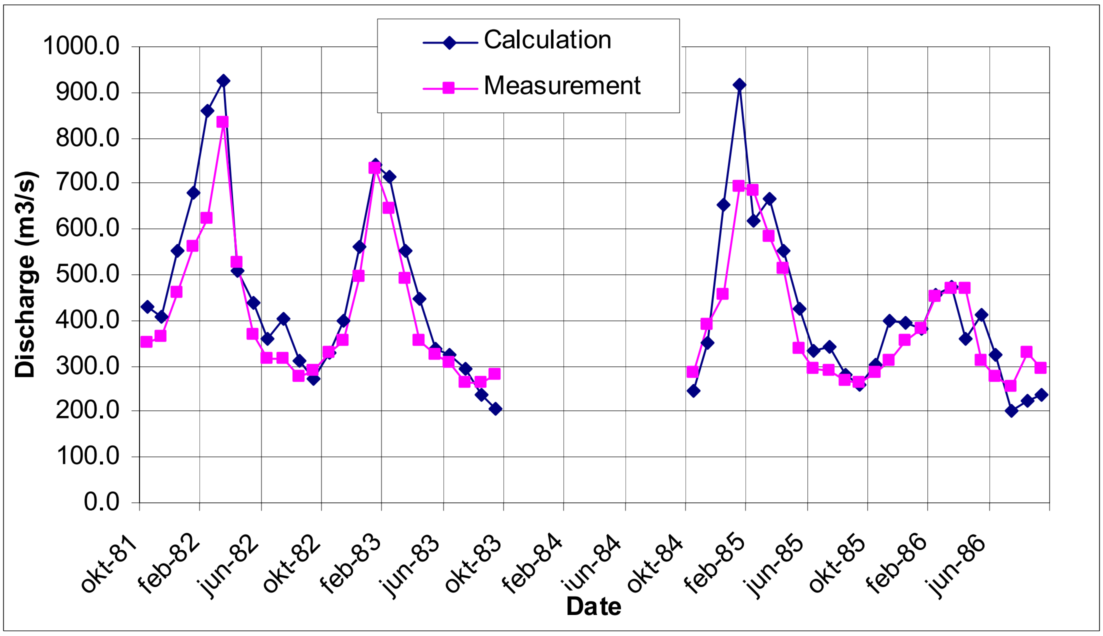

Figure 6.13 Calculated and measured average monthly discharge at Coxim for two periods

6.4 Hydrological scenarios

Now the model is ready, it can be used to answer the question in what extent the inundations have been caused by the increase of rainfall and/or the change of vegetation. This is done by creating and comparing scenarios. A reference scenario represents the historical situation and scenarios will be variants on that, representing imaginary and current situations. The scenarios and their attributes are shown in table 6.6. The scenarios won't be compared to measurements anymore, but only to each other.

Table 6.6 Attributes of scenarios

Scenario	Meteorological conditions	Land use conditions
Reference scenario	dry	no cultivation
Scenario 1	wet	no cultivation
Scenario 2	dry	cultivation
Scenario 3	wet	cultivation

The land use settings and meteorological series that have been assigned to the scenarios are based on measurements/observations made in the beginning of the 1970s representing the historical state at the end of the 1980s and beginning of the nineties representing the current state (Table 6.7, 6.8)

Table 6.7 Features of meteorological settings used in the scenarios

Meteorological condition	Modelling period	Average annual rainfall (mm)*
dry	1-okt-1969 to 30-sep-1971	1131
wet	1-okt-1986 to 30-sep-1988	1545

* Average over model area

Table 6.8 Features of land use settings used in the scenarios

Land use condition	Corresponding year	Total area of cultivated land (km²)	Relative area of cultivated land*
no cultivation	1974	1.737	1.6%
cultivation	1991	28.531	26.7%

* Relative to total model area: 106.838 km² (cultivation occurs mainly at the Planalto)

Calculation of the scenarios has been carried out with an average meteorological year prior to the calculation period for the adjustment of surface- and groundwater levels. Comparison of the results of the scenarios is not restricted to the availability of measurements. For the surface water regime comparisons will be made at four locations. The locations are shown in figure 6.14 represented by the subcatchment(s) and the present measurement station at that location. For each station the series of average monthly discharge are given in the figures 6.15 to 6.18 for all scenarios. The figures of discharge series have been standardized to the dates of the historical state.

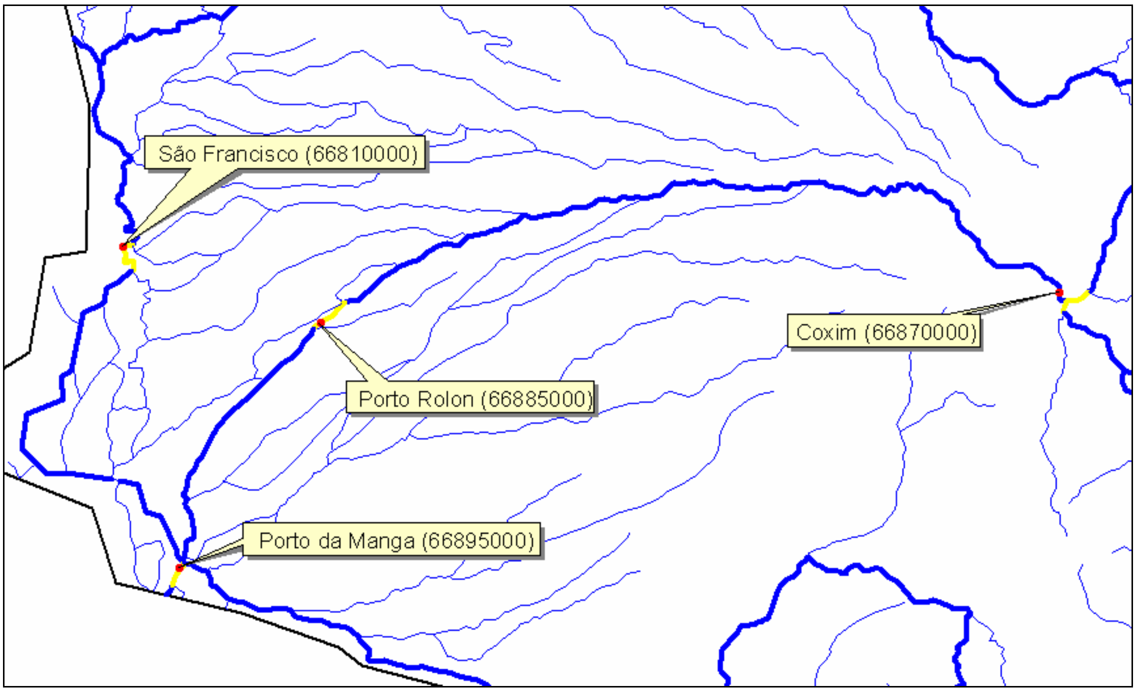

Figure 6.14 Locations for which the calculated discharge of the scenarios will be compared

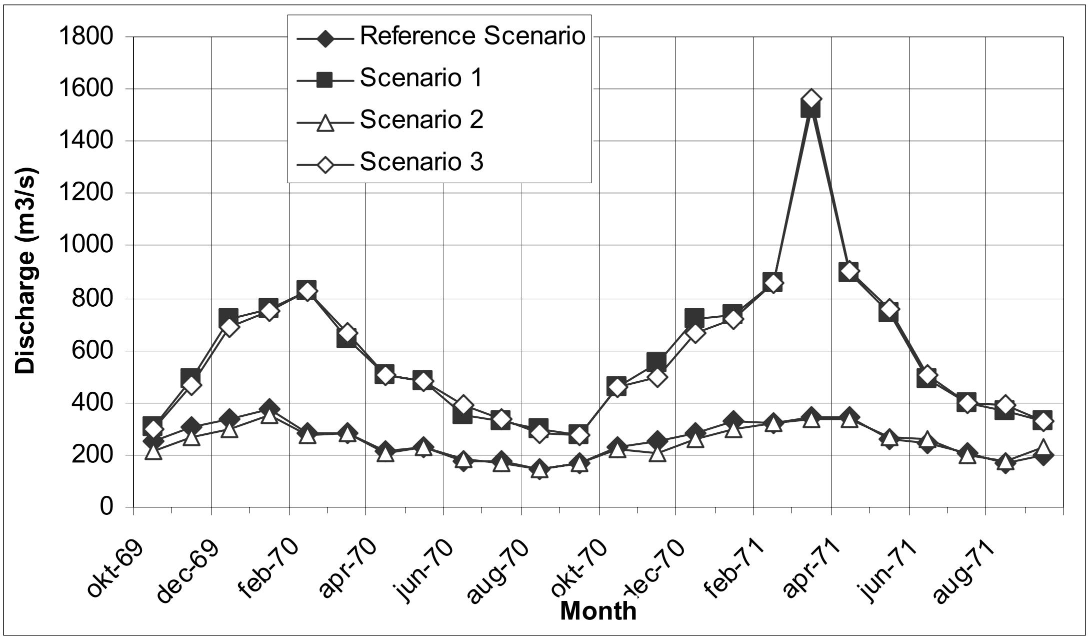

Figure 6.15 Average monthly discharge at Coxim for the scenarios

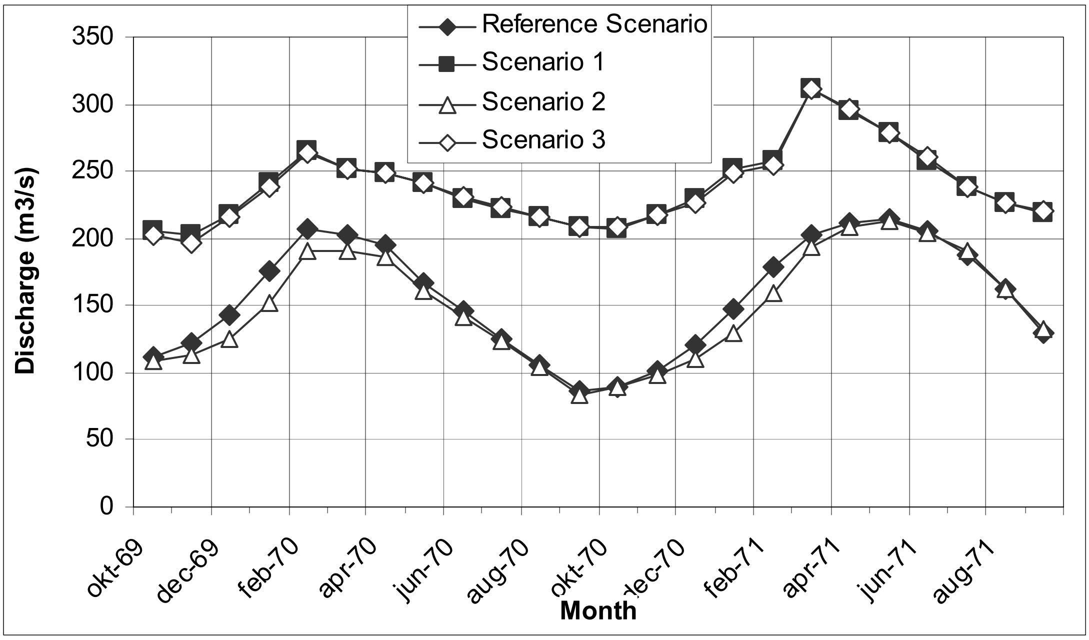

Figure 6.16 Average monthly discharge at Porto Rolon for the scenarios

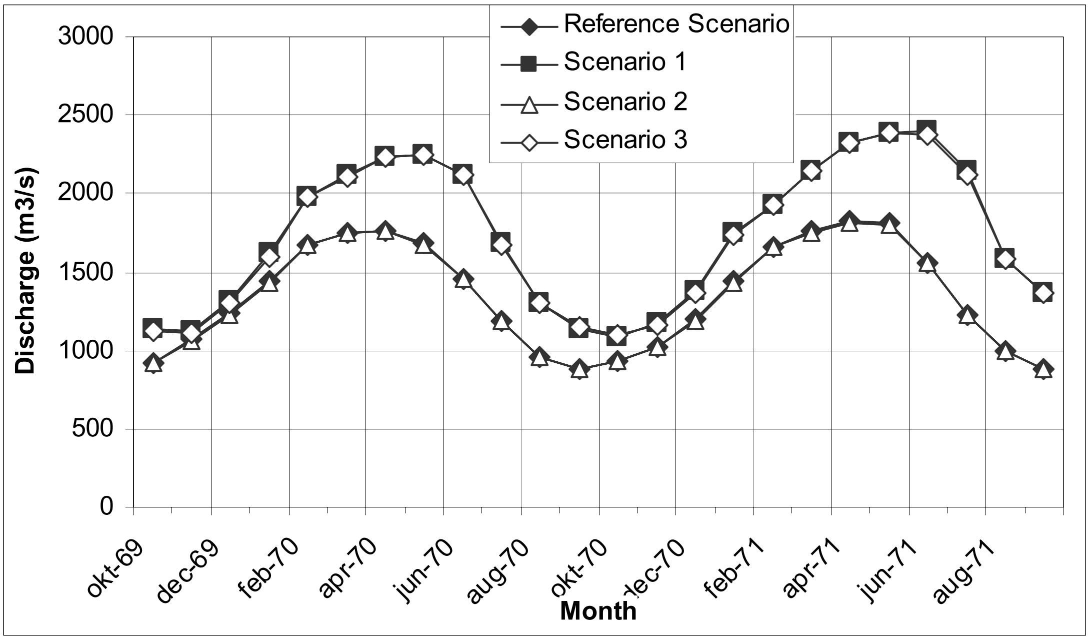

Figure 6.17 Average monthly discharge at São Francisco for the scenarios

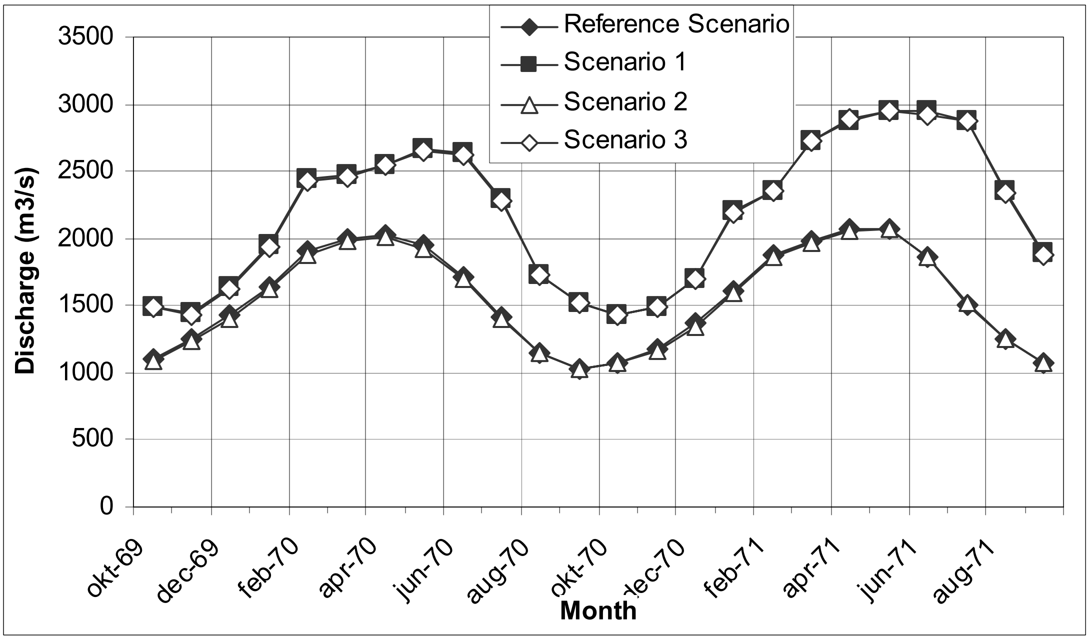

Figure 6.18 Average monthly discharge at Porto da Manga for the scenarios

The results show that the increase of precipitation has caused an increase of discharges in the rivers in the Pantanal. Against all expectations the cultivation at the Planalto did not result in an increase of discharge in these rivers, in fact a little decrease is calculated. A second feature of the discharge curves is the delay of flood peaks in the scenarios with high rainfall. At Porto Rolon the discharge peak seems to come still slightly earlier in case of increased precipitation, but at the examination points along the Rio Paraguai, the peak is clearly delayed compared with the reference scenario.

For the stations in the Pantanal the day to day variation is very small, inducing that a single calculated discharge doesn't differ that much from the monthly average. At Coxim the rise and fall of discharge peaks is a very frequent appearing phenomenon. This might also be the result of the fact that the discharge at this location along the Taquari River is approximated with the sum of the discharges of the two upstream rivers. Using monthly averages gives a better possibility to compare the general characteristics of the discharge series, but doesn't say anything about extreme events. In this case, however, insight in the general characteristics is preferred.

By means of the model the effects of increase of rainfall and cultivation have been estimated with good results, although, the effects on the groundwater levels and the relation with the inundations haven't been shown yet. At the end of the calibration, the statement is made, that given the current situation, it is hard to set value on the calculated groundwater levels and inundations. To have still any result, the calculated inundated area is shown in figure 6.19. Dates of scenario 1 and 3 have been converted to dates of the period 1970-1971.

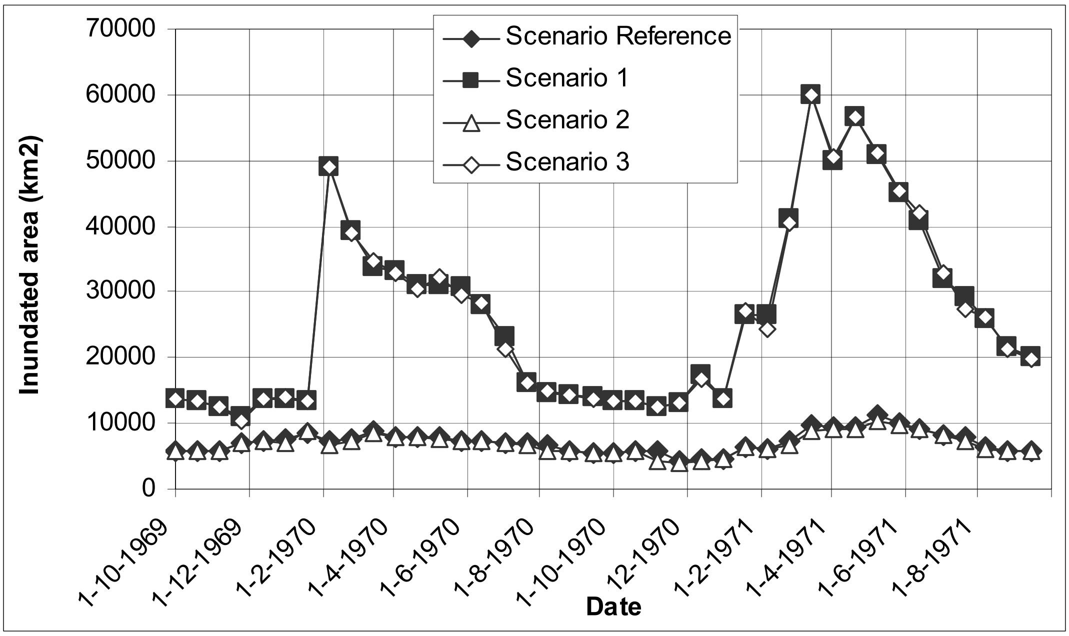

Figure 6.19 Calculated total inundated area in the model area (104.489 km², exclusive boundary nodes)

The graphs of inundated area show the same results as the discharge curves; only the increased rainfall causes an increase in total inundated area. However, the increase is significantly bigger. In the dry scenarios the average inundated area is around the 7.000 km^2, while for the wet scenarios this value has increased to 26.000 km^2. Hence, an increase of precipitation of 37% has resulted in an increase of inundated area of 271%. A notification must be made that the calculated inundated areas shown in figure 5.6 are probably overestimated, saying this with common sense, but the effect is still quite clear. On the other hand, the non-linear increase of effects has also been observed by for example the average discharge at Coxim. The fact that discharges of the Paraguai River show the lowest increase might also be the result of the boundary conditions.

The conclusion can be made that increase of precipitation has large effects on the hydrology of the Pantanal, but the minor changes caused by the cultivation cannot be completely explained. The most logical explanation is that the conversion from savannas to cultivated land did not have a big impact. Looking at the features that Simgro model attributes to these land use types, the difference is indeed quite small. A possible reason for the even lower discharges in the case of the presence of cultivated land might be the higher crop factor and hence the higher evapotranspiration of this land use type. Change into forest would have a much bigger effect.

6.5 Conclusions and recommendations

Calculations with the SIMGRO model have shown that discharges in the rivers in the Pantanal and the inundated area increase significantly as a result of a (even a slight) increase in rainfall. The modelled increase of over the model averaged annual rainfall had been from 1.131 mm to 1.545 mm (37%), resulting in an increase of the discharge of the Rio Taquari at Coxim of 130% and at Porto Rolon of 54% and an increase of total inundated area of even 271% averaged over the year (mostly in wet season). On the other hand the change of land use from savannah to cultivated area did make hardly any difference. As a matter of fact, the total discharge at Coxim and Porto Rolon dropped with 4%, as well as the annual average of total inundated area. Hence, it seems to be that the observed increase of discharges and inundations are likely to be caused by the observed increase of rainfall and change in evapotranspiration.

The simplification and the use of assumptions in the model schematization were noticeable during the sensitivity analysis and the calibration. The model showed weaknesses at the groundwater levels and especially inundations that tended to be determined by the schematization of the subcatchments rather than the near environment. Up to this, the lack of measured groundwater levels and inundations hampered the improvement of the model by means of calibration.

Sensitivity analysis has been carried out for parameters that had been schematized based on mostly assumptions. These parameters are: hydraulic conductivity of soil, stage-discharge relationships and drainage resistance. Comparisons were made for the discharges at Coxim that in the first place showed small differences for the changes made to the parameters.

The final model was satisfying. Estimates of the discharges at Coxim were most satisfying; the average monthly discharge deviated 14% of the measurements on the average and the series had an overestimation of 11%. At Porto Rolon and São Francisco the resemblance between measured and calculated discharge is a even smaller. The underestimations of the total discharge are 18% and 26% respectively and the seasonal variance shows some deviations as well (most of these deviations from the measurements can most likely be attributed to the lack of knowledge about discharge distributions and surface water inflow at the boundaries). The total inundated area in the model varies (seasonally) from 7.000 km^2 in dry periods to 35.000 km^2 at the peak (of a total area of 105.000 km^2).

The model turned out to be successful in the determination of the causes of the inundations. The most likely future use is the use of the model as an instrument to test measures against flooding. The model is physically based, what increases the reliability of calculations carried out for unknown situations.

7 Impact modelling of scenarios on vegetation and fauna

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7.1 Introduction

The environment surrounding us is subject to a continuous development. Planning new developments may be at the expense of nature or in favour of nature development. Planners wonder what the consequences of their scenarios for nature are or what kind of nature might develop. Interesting is to know which of the different scenarios made is the most favourable one for nature. Evaluating these scenarios on a qualitative level is common. However, a more spatial presentation is very time consuming. A good comparison has to be done in the same consequent way. Models made to do this are the so-called Decision Support Systems (DSS). They help planners and policy makers to make choices in the spatial arrangement.

The use of a DSS also facilitates the evaluation of certain measures and enables experimenting with slightly different measures and/or planning targets. This is the cyclic planning (Figure 7.1). Furthermore, the DSS is applicable on different scales, varying from the larger policy-making level (e.g. 1:100.000) to the small design level (e.g. 1:10.000).

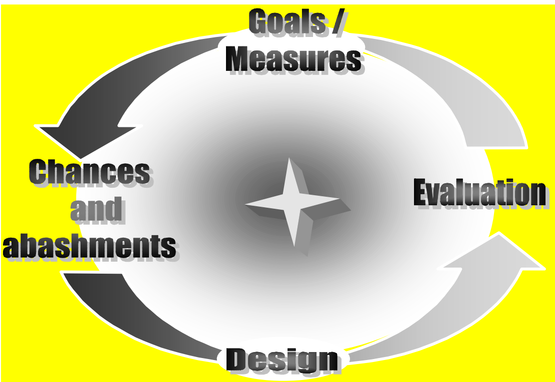

Figure 7.1 Cyclic planning procedure: the base for a DSS

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In 1996 the former DLO-Staring Centre (now: DLO-Alterra) developed LEDESS (Landscape Ecological Decision & Evaluation Support System) which was used in several projects (Harms et al 1991). LEDESS is a GIS based expert system. It is used to assess and evaluate the effects of land use changes on land cover and nature. LEDESS confronts GIS maps of the existing landscapes with proposed measures and ecological knowledge. The results are GIS maps and tables of expected land cover, vegetation and fauna distribution. LEDESS evaluates scenarios on their ecological and/or economic effects. In this way decisions can be made what land use developments can be expected. In section 7.2.1 the concept of LEDESS is explained.

In this project the evaluation of scenario impact on fauna has been done with the LARCH-model (Landscape Analysis and Rules for the Configuration of Habitat). LARCH calculates the population viability analysis of scenarios and the network function for fauna species in a landscape. In section 7.2.2 the theoretical concept underlying the LARCH assessment is explained.

The aquatic fauna is analysed separately. The character of these species, the way they use their environment and the available data do not match well to be used in scenario analysis. The main problem is that quantification or areal distribution of the fish habitat cannot be estimated on the basis of the data available. The theoretical background and further considerations are treated in section 7.2.3.

7.2 Method

7.2.1 LEDESS-Pantanal model

Clear definitions are necessary when trying to put landscape or nature into a model. Basic questions are the definition of regional characteristics the processes that drive the landscape. A model is always a simplification of the real world. To make calculations possible model schematization has to be made. Therefore model characteristics have to be defined and positioned in space and time. The model characteristics can be described in system attributes. For actual model calculation, a typology of all attributes has to be developed and combined with data and calculation rules.

The landscape-ecological modelling in LEDESS is based on an ecosystems classification. Four components are considered for the applying of the LEDESS concept in the Pantanal::

1 Ecotopes: homogeneous units defined on basis of land cover or vegetation types and physiotopes;
2 Physiotopes: homogeneous units defined on basis of abiotic patterns and processes;
3 Vegetation structure types: consisting of homogeneous units of the same vegetation structure; the can be floristically divers
4 Habitats: spatial units that can support fauna organisms for at least part of its life cycle

Interactions between the components have been taken into account. The relations are topological (vertical) and chorological (horizontal). Processes are present as a derivation from the different ecosystems. This means that the model is a spatial model and not a process model so processes are not explicitly part of the model but their results are presented in the different scenarios. To define relations between scenarios a system of knowledge tables, decision trees and typologies link the spatial components of the model.

The concept of the ecotope originates from landscape ecology. An ecotope is defined as "a physically limited ecological unit, of which composition and development are determined by abiotic, biotic and anthropogenic aspects together". Ecotopes are homogeneous units on the scale of the landscape under consideration, identifiable by their similarities and differences in geomorphologic and hydrological characteristics, vegetation structure and land use (Figure 7.2). Within the model, ecotopes are unique combinations of vegetation structures and physiotopes.

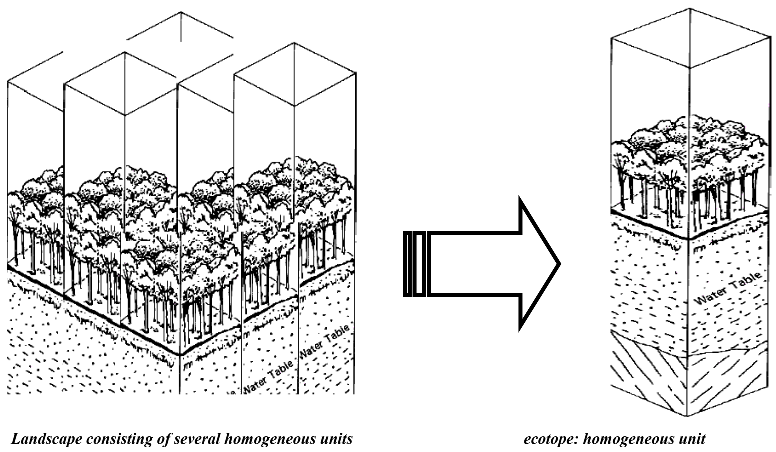


Figure 7.2 The ecotope concept, used in the LEDESS-model: landscape consisting of several homogeneous units at the used scale

The spatially homogeneous elements concerning abiotic circumstances, relevant for vegetation development are named physiotopes (Figure 7.3). Differentiating characteristics are the abiotic processes, ground water levels and substrates. In other words, if management and stage of development are the same, then the physiotope and ecotope is the same physical unit.

Considering vegetation development, a distinction must be made between vegetation structure types or life form types and ecotopes. Vegetation structure types are areas, at a specific scale, with a homogeneous vertical and horizontal vegetation structure and intensity of management (Figure 7.3). They can be heterogeneous in vegetation composition. Together with the physiotopes they form the ecotopes.

The development of the vegetation structure can be simulated in the model based on abiotic conditions, management and the number of years that the vegetation is allowed to develop. A second, simpler option is the snapshot development: the vegetation development is directly translated into a vegetation structure type of a next phase.

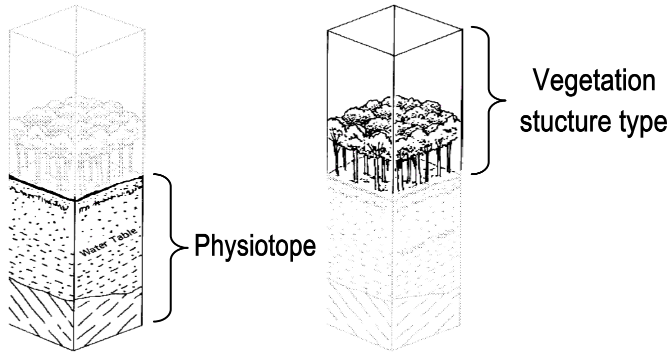


Figure 7.3 Ecotopes consisting of Physiotopes and Vegetation structure types

Habitat is used as a spatial unit in which all fauna species-specific demands can be placed. It is here defined as a spatial collection of ecotopes which can support fauna organisms for at least a part of its life cycle. Habitat types are the input for the LARCH model population viability analysis (Landscape Analysis and Rules for the Configuration of Habitat). The (changed) ecotopes in the scenarios result in changes in the available habitat and its configuration. With LARCH, the effect of these changes on the viability of species populations can be assessed. Besides that, an assessment of the network function of species in a landscape has been made operational.

The purpose of the LEDESS-Pantanal model is to create a dynamic ecotope scenario model of the Pantanal-Taquari-area. The model intends to evaluate ecological effects of variations in the flooding regime within the whole Pantanal-area and land use changes in the alluvial fan of the Taquari river. These spatial scenarios can be based on changes in flooding regime, on economical driving factors, or socio-political arguments such as nature conservation considerations. The typology for the Pantanal-ecotopes is based on:

- The basic river processes that drive the Pantanal system;
- Land use and management.

The geographical confinement is the alluvial fan of the Taquari River.
Based on these principles the ecotopes are classified on three general characteristics, influencing physiotopes, vegetation and fauna:

1. **Morphodynamics:** Mechanical forces exercised by water and sediment (erosion, transport and deposit of sediment, flow of water and surge); to model these morphodynamics for the Pantanal new geomorphology-data had to be developed.
2. **Hydrodynamics:** Physiological and chemical effects of water (duration, depth and time of flooding, as well as the type of the water); In the LEDESS-Pantanal model duration has been specified by the use of satellite data and the use of hydrological models. The type of water (rain, flooding or groundwater) has been modelled and combined from several models and data sources L
3. **Land use/vegetation dynamics**: Effects of mainly by human intervention i.e. conscious landscaping and management from grazing or rough pasture management to intensive agricultural use). In addition, the developing from pioneer vegetation to forest or savannah after natural set back of vegetation is part of this factor. For the Pantanal, satellite data has been combined with expert knowledge and existing

vegetation maps to model current vegetation, as well as the change of vegetation type under scenario conditions.

To perform model calculations, a typology for the system attributes has been defined and combined with data and calculation rules. These data and knowledge sources are related in a scheme for scenario calculation. This allows calculating for different scenarios ecotope maps of the Pantanal-Taquari area based on morphodynamics, hydrodynamics and vegetation dynamics.

Ledess-Pantanal is using the OSIRIS spatial modelling environment to set up the structure for the model (Figure 7.4). To realize a structured modelling environment all system attributes in LEDESS-Pantanal have been categorized. The model for Pantanal-Taquari contains abstract system attributes (e.g. vegetation types, physiotopes) defining ecotopes. The system attributes can be divided into two main classes:

Basic attributes, describing the fixed and variable start attributes the model works with

1 Fixed model attributes:
   a Fixed attributes the model needs to calculate the end result. These attributes will not change in the different scenarios
   b Parameter attributes: The model variables.
2 Calculated attributes
   a Ecotopes Map
   b Vegetation Map
   c Habitat Suitability maps
   d All the temporary calculation results (Figure 7.5)

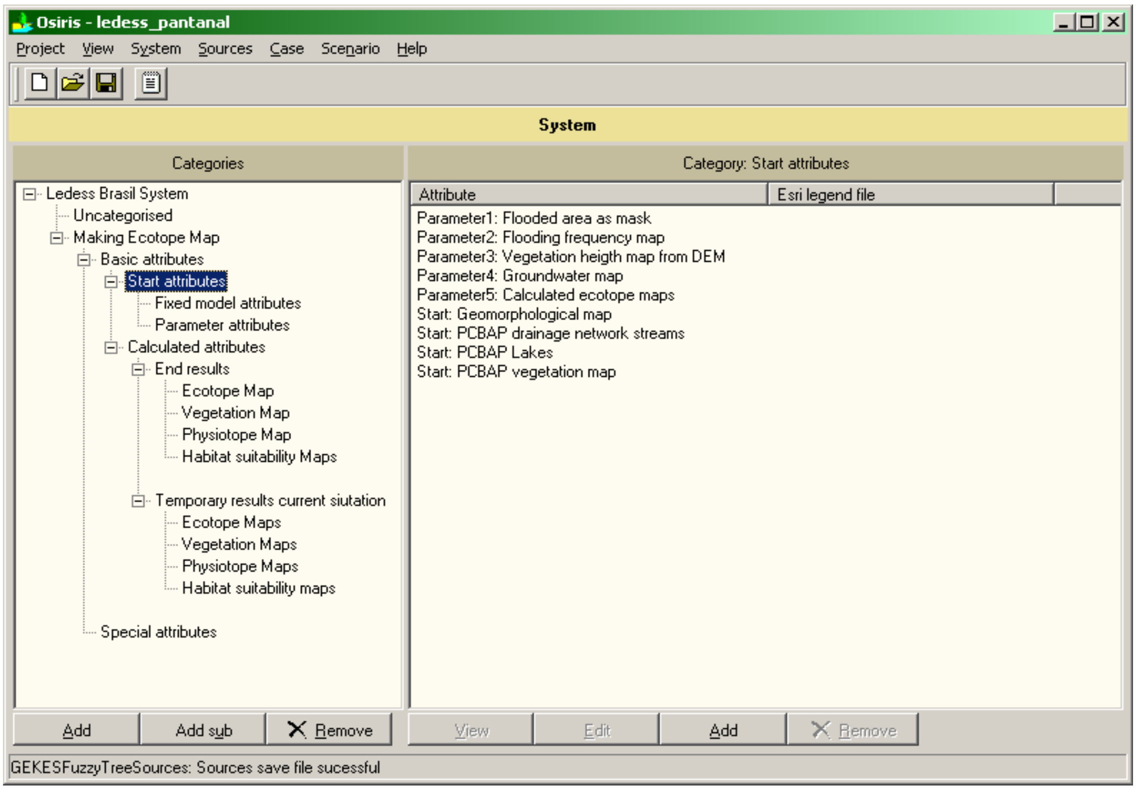


Figure 7.4 Structure of system attributes for model calculation (Verwey, 2004).

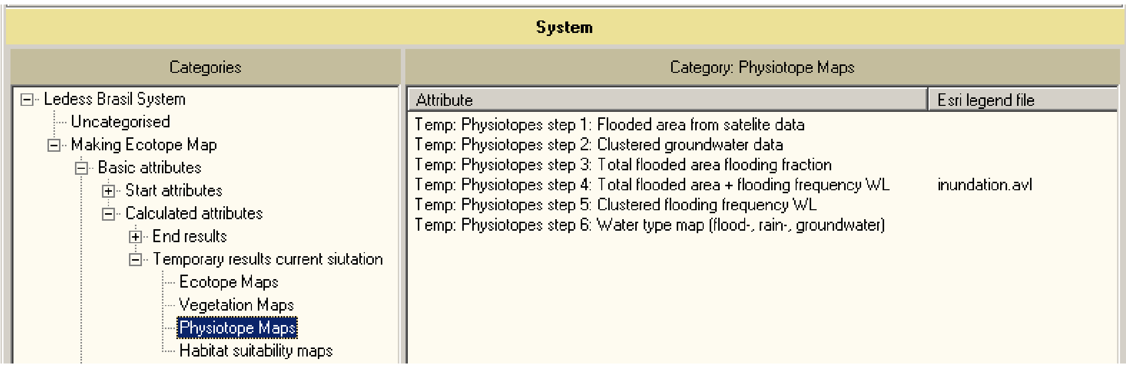


Figure 7.5 Example temporary attributes (calculation steps towards physiotopes) for calculation of the End Results

In the real world the main input factors (vegetation structure, physiotope, measures/targets) do not consist of distinct classes. They are part of a continuous gradient. However, for use in LEDESS they need to be classified as they are confined to map units. For the definition of classes an underlying typology has to be developed.

To characterise the ecotopes knowledge is required about the species and their relation with the ecotopes. The typology that has been used as the basis for the attributes of landscape model has been developed in two workshops in Corumbá MS (Brasil). Table 7.1 shows the basic definition of ecotopes based on vegetation structure types, flooding frequency and flooding type. The final typology of the ecotope map is presented in Table 7.2

Table 7.1 The typology final vegetation, physiotopes and ecotopes.

		Flooding frequency (months/year)						Flooding type (seasonal)		
	NAME_VEG	dryer	never	>0-3	4-6	7-9	permanent	rain	river	ground-water
1	Galery forest			x	x	x			x	
2	Semi Decidual Forest	x	x							
3	Form. pioneiras (Transicao)				x				x	
4	Savana Forested (Cerradao)	x	x							
5	Savana arboreal (Cerrado)		x	x				x	x	
6	Savanna Gramineo lenhosa			x	x			x	x	
7	Savana Gramineo lenhosa + arboreal (Cerrado)		x							
8	Pioneir vegetation (influencia fluvial)				x	x	x	x	x	x
9	Area cultivada		x	x				x		
10	baia			x	x	x	x	x	x	x
11	corixo				x	x	x	x	x	x
12	oxbows						x		x	
13	salina			x	x	x	x	x		x
14	river						x	x	x	x
15	vazante			x	x	x		x	x	
16	Bare soil (NO VEGETATION)	x	x	x	x	x			x	
17	Chaco povre on clay soils	x	x	x	x	x	x			

Table 7.2 Final typology of the ecotope map

Theme: Ecotopes (physiotopes x vegetation types)

Class name	Class v
2_Galery forest_4-6	2
3_Semi Decidual Forest_never	3
4_Form. pioneiras (Transicao)_4-6	4
5_Savana Forested (Cerradao)_never	5
6_Savana arboreal (Cerrado)_never	6
7_Savana arboreal (Cerrado)_>0-3	7
8_Savanna Gramineo lenhosa_>0-3	8
9_Savanna Gramineo lenhosa_4-6	9
10_Savana Gramineo lenhosa + arboreal (Cerrado)_never	10
11_Pioneir vegetation (influincia fluvial)_4-6	11
12_Pioneir vegetation (influincia fluvial)_7-9	12
13_Pioneir vegetation (influincia fluvial)_permanent	13
14_Area cultivada_never	14
15_Area cultivada_>0-3	15
16_baia_>0-3	16
17_baia_4-6	17
18_baia_7-9	18
19_baia_permanent	19
20_corixo_4-6	20
21_corixo_7-9_	21
22_corixo_permanent	22
23_oxbows_permanent	23
24_salina_>0-3	24
25_salina_4-6	25
26_salina_7-9	26
27_salina_permanent	27
28_river_permanent	28
29_vazante_>0-3	29
30_vazante_4-6	30
31_vazante_7-9	31
32_Bare soil (NO VEGETATION)_never	32
33_Bare soil (NO VEGETATION)_>0-3	33
34_Bare soil (NO VEGETATION)_4-6	34
35_Bare soil (NO VEGETATION)_7-9	35
36_Chaco_povre_never	36

ecotopes

Theme: project vegetation

Class name	Class v
1 - Galery Forest	1
2 - Semi Decidual Forest	2
3 - Form. pioneiras (Transicao)	3
4 - Savana Forested (Cerradao)	4
5 - Savana Arboreal (Cerrado)	5
6 - Savanna Gramineo lenhosa (open low)	6
7 - Savana Gram. lenh. + arb. (Cerrado, dry open)	7
8 - Pioneir vegetation (influincia fluvial)	8
9 - Area cultivada	9
10 - Baia	10
11 - Corixo	11
12 - Oxbow	12
13 - Salina	13
14 - Vazante	14
15 - River	15
16 - Bare Soil	16
17 - Chaco povre	17

land cover/vegetation types

Theme: Physiotopes

Class name	Class v
1 - River & Rain- not flooded	1
2 - River & Rain - flood >0-3	2
3 - River & Rain - flood 4-6	3
4 - River & Rain - flood 7-9	4
5 - River & Rain - flood permanent	5
6 - Rain - not flooded	6
7 - Rain & Groundwater - not flooded	7
8 - Rain &/or Groundwater - water on surface >0-3	8
9 - Rain &/or Groundwater - water on surface 4-6	9
10 - Rain &/or Groundwater - water on surface 7-9	10
11 - Rain &/or Groundwater - water on surface permanent	11
12 - River & Rain &/or Groundwater - not flooded	12
13 - River & Rain &/or Groundwater - flood >0-3	13
14 - River & Rain &/or Groundwater - flood 4-6	14
15 - River & Rain &/or Groundwater - flood 7-9	15
16 - River & Rain &/or Groundwater - flood permanent	16

physiotopes

In the Ledess-Pantanal model decisions are made on the basis of consist of knowledge and data that quantify and/or qualify a system. The framework behind Ledess-Pantanal supports five types of sources:

- Esri grids;
- Esri Avenue scripts;
- Knowledge matrices;
- Decision trees;
- Fuzzy logic trees.

A source can be an Esri grid with land use data, or a knowledge matrix that translates land use to landscape structure elements. Every source type has its own specific way to be added, viewed and altered. The next sections display the view and alter possibilities of every source type. In more detail a description of a Knowledge matrix is given.

A knowledge matrix connects to one or more system attributes (Figure 7.6). Each knowledge matrix has a unique name and is visualized in a table. Every dimension is related to an attribute. Tables are defined for two dimensions Higher dimensions are considered to be constant. A knowledge matrix is defined on the basis of system attributes. The resulting range of a knowledge matrix is also based on a system attribute and can correspond with a system attribute in one of the dimensions.

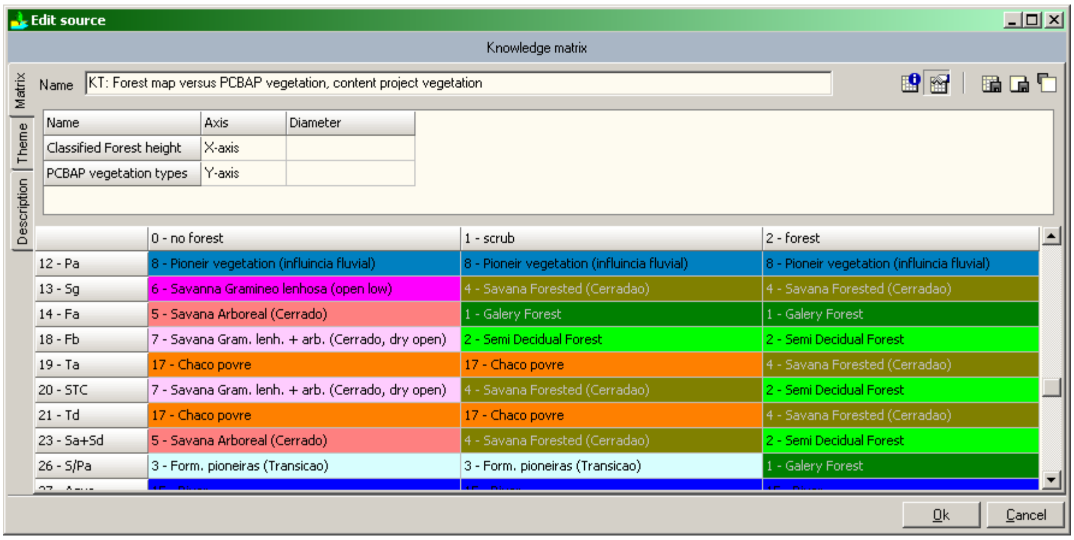


Figure 7.6 Example of a knowledge table in LEDESS-Pantanal. The first column represents PCBAP vegetation legends.

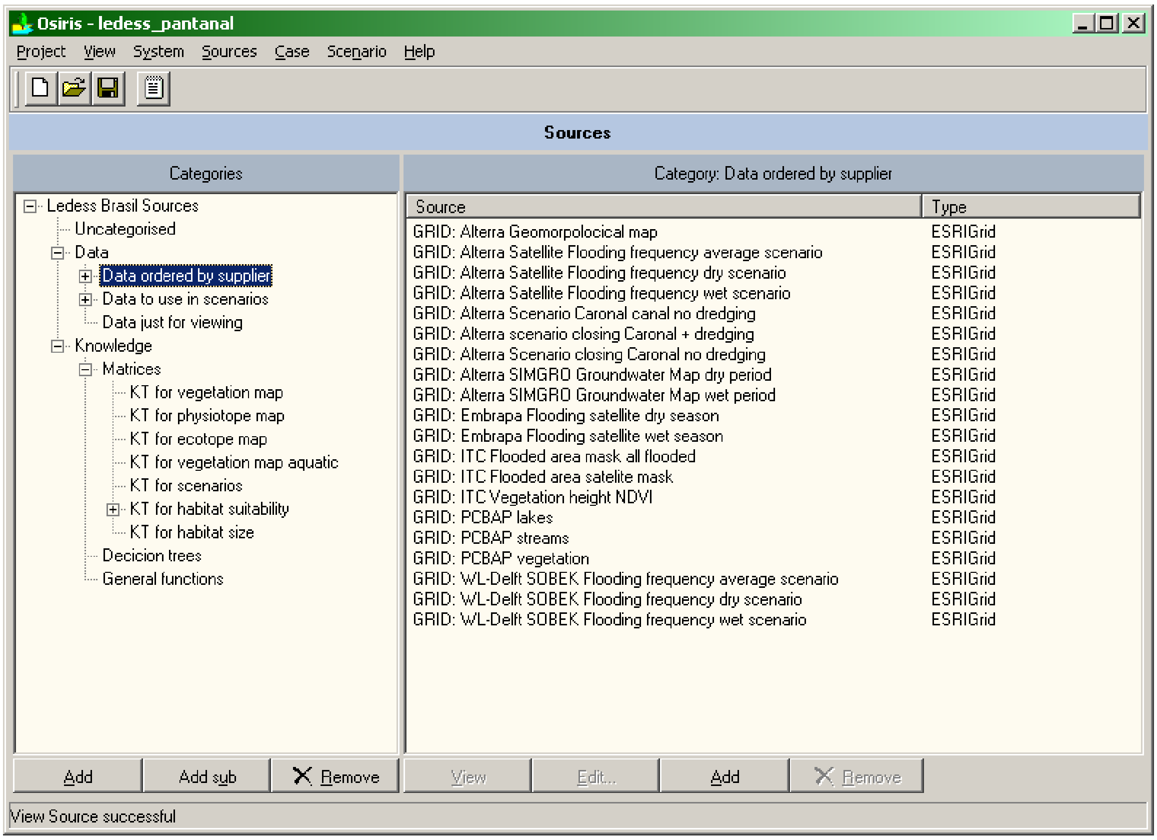


Figure 7.7 Sources: Data and Knowledge

		animal'name		Red brocked deer	White lipped pecca	Tuiuiu (Hoary Fox	Jacare		Marsh deer	Pampas deer	Ema	Giant anteater		Cattle	Giant otter		Jaguar	Yellow anaconda
		RPU		3	0.2		25		0.8	5	0.2	1		3.2	0.08		0.04	6
ID1	ID2	NAME	FLOOD															
1	1	Galery forest	>0-3	0.5	1		1	B				1	R		1	BR	1	0.5
2	1	Galery forest	4-6	0.1	1							0.5	R		1	BR	1	0.5
3	2	Semi Decidual Forest	never	1	1		1	B				1	R	0.5			1	
4	3	Form. pioneiras (Transicao)	4-6		1		1	FB						0.5			1	1
5	4	Savana Forested (Cerradao)	never	1	1		1	B				1	R	0.5			0.5	
6	5	Savana arboreal (Cerrado)	never	0.5	1	0.5				0.5	1						0.5	
7	5	Savana arboreal (Cerrado)	>0-3		0.1	0.1	0.5	F	0.1	0.5	1	0.5		0.5				1
8	6	Savanna Gramineo lenhosa	>0-3		0.5	1	0.5	F	0.1	1	1	1	F	1				1
9	6	Savanna Gramineo lenhosa	4-6		0.1		0.5	F	1	1	0.5	1	F	1				1
10	7	Savana Gramineo lenhosa + arborea	never			0.5				0.5	1	0.5	F	0.5			0.5	
11	8	Pioneir vegetation (influincia fluvial)	4-6															
12	8	Pioneir vegetation (influincia fluvial)	7-9															
13	8	Pioneir vegetation (influincia fluvial)	permanent															
14	9	Area cultivada	never															
15	9	Area cultivada	>0-3															
16	10	baia	>0-3															
17	10	baia	4-6															
18	10	baia	7-9															
19	10	baia	permanent															
20	11	corixo	4-6															
21	11	corixo	7-9															
22	11	corixo	permanent															
23	12	oxbows	permanent															
24	13	salina	>0-3															
25	13	salina	4-6															
26	13	salina	7-9															
27	13	salina	permanent															
28	14	river	permanent															
29	15	vazante	>0-3															

Figure 7.8 New knowledge developed in expert workshops

The most important data sources have been (Figure 7.7)
- PCBAP vegetation map (Embrapa)
- Vegetation height map (derived from DEM) (ITC)
- Satellite flooding frequency maps and max. flooded area (Alterra, Embrapa, ITC)
- New Geomorphologic map (Alterra)
- New Groundwater map (Alterra)
- Model flooding frequency SOBEK (WL-DELFT)

Knowledge on relationships between ecotopes, physiotopes and on processes has been developed in two workshops with local experts on land cover and species in March and August 2004 (Figure 7.8).

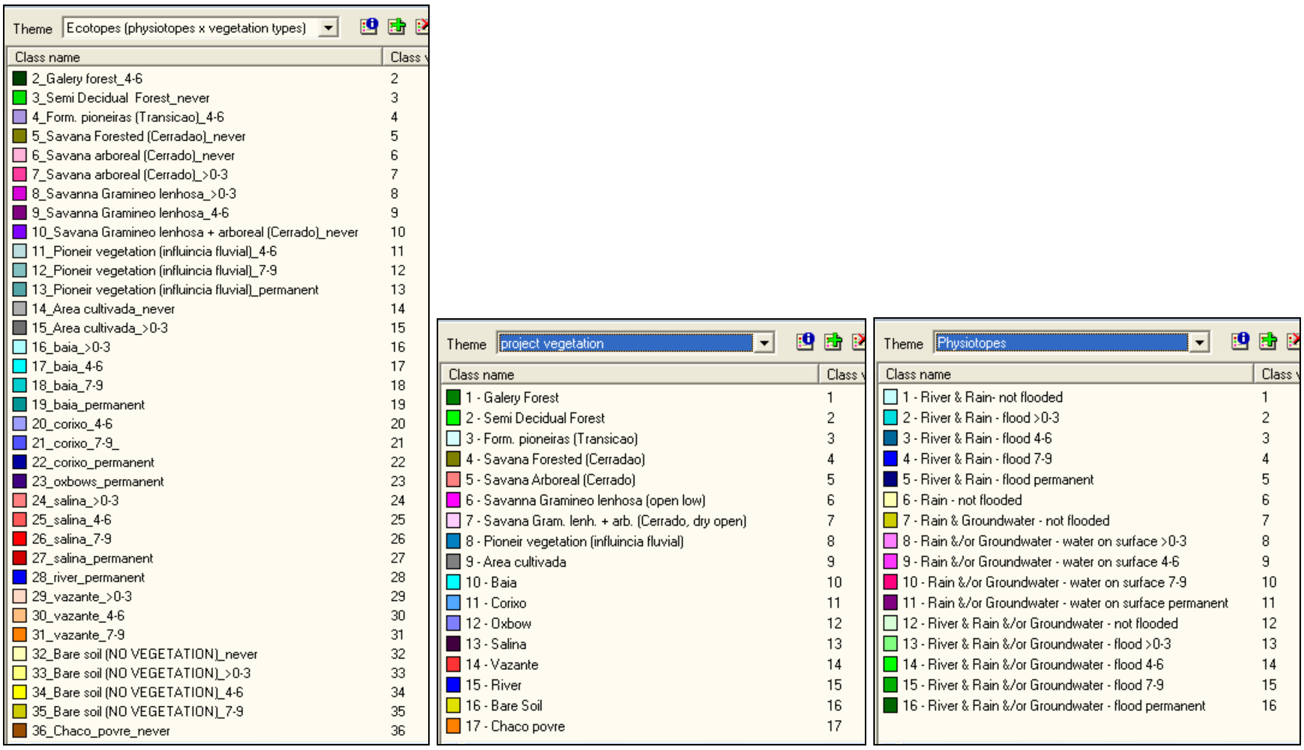


Figure 7.9 The final Ecotope categories based on the original data and the results of the expert workshops. In the rows the land cover/vegetation types are given, in the columns the major flood types and characteristics as determining factors.

The final categories of the ecotope map as developed on the sources and the expert workshops are given in Figure 7.9. The ecotope map is based on a generalisation of land cover and vegetation types and on the major physical determinant: flooding. Flooding duration and origin of the water are the major characteristics.

The model consists of system attributes and sources. A "Case" fixes the calculation scheme in which system attributes are connected to sources, and necessary attributes of sources are connected to system attributes. A group of related connections together is called a calculation scheme. This calculation scheme is used for the calculation of each scenario. In the LEDESS-Pantanal model, a case has been build to determine how the ecotopes will change when abiotic parameters like flooding frequency will change. Another part of the case describes the impact of these changed ecotopes on the fauna.

The case is the basis of all scenarios. All connections between system attributes and sources that are made in a case are used in the calculations of a scenario. Cases can be linked into a higher level. In general the calculation scheme contains the following elements:

- Connected system attribute;
- Unconnected system attribute;
- Required attribute;
- Source with required attributes;
- Source without required attributes

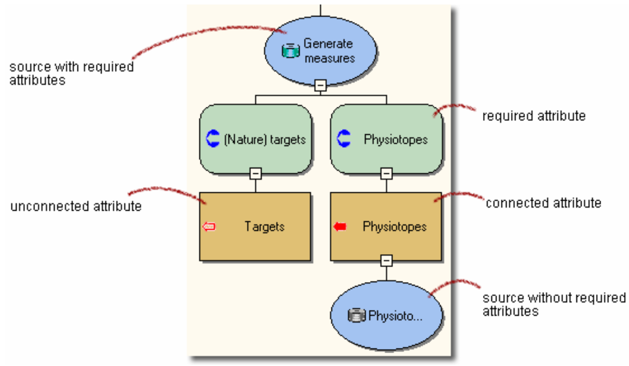


Figure 7.10 Example of elements in the calculation scheme

For the case of the Pantanal the model consist of five important parts
- Creation of a final vegetation map (Figure 7.11)
- Creation of a final physiotope map
- Aquatic ecotopes
- Combining 1-3 to final ecotopes
- Habitat suitability of ecotopes for fauna (knowledge storage)

Final vegetation has been created from
- vegetation height DEM (parameter)
- Geomorphologic map (forest type, bare soil)
- PCBAP vegetation map (basic vegetation types)

Knowledge on relationships between geomorphology and vegetation types and between the forest map and the vegetation map has been used to further determine new maps.

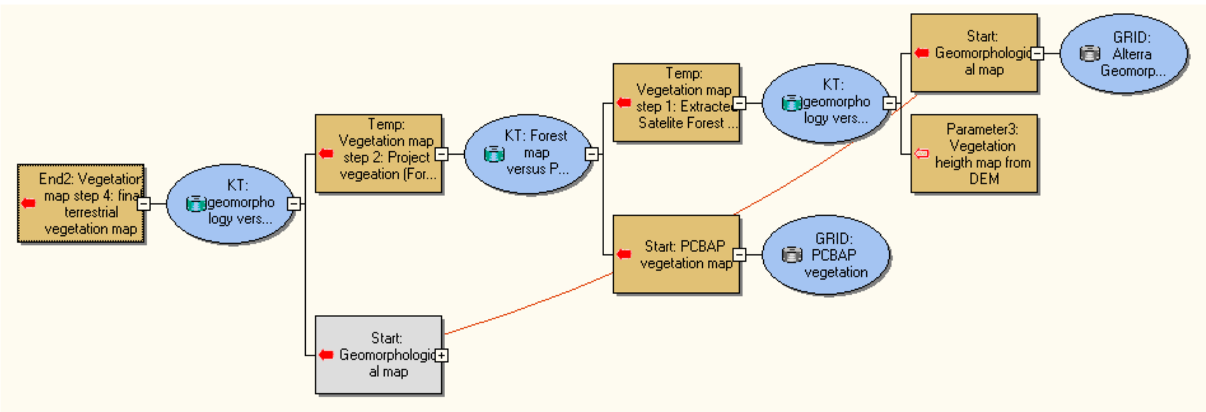


Figure 7.11 Case for Final vegetation map

The final map for physiotopes is actually a flood duration and flood type map. It has bee created from (Figure 7.12):
- Groundwater map (parameter)
- Maximum flooded area (parameter)
- Flooding frequency (parameter)
- Geomorphologic map (water type in combination with groundwater and flood frequency)

Expert knowledge has been used to determine flooding duration related to water types; research results have been used to determine flood frequency and flood duration as well as the area under influence of different water sources.

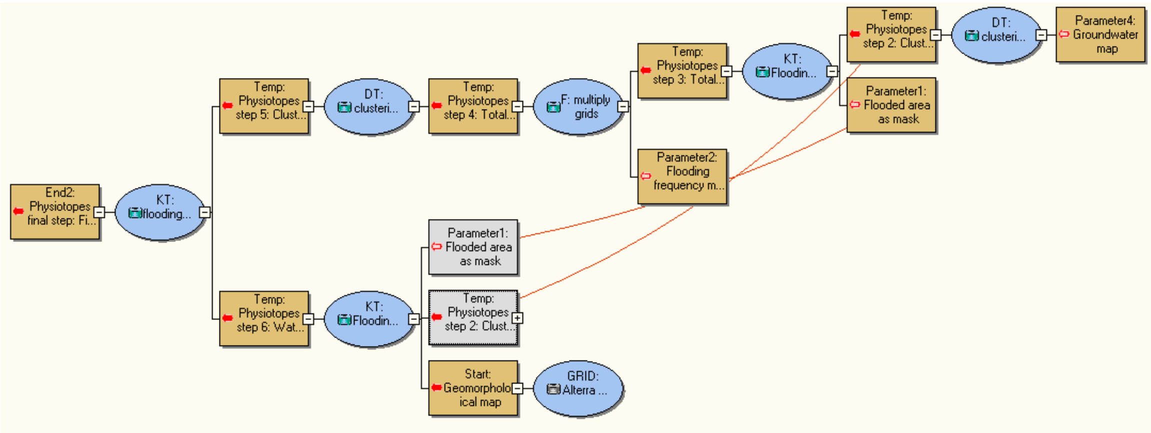


Figure 7.12 Case for Final physiotope map

The final ecotope map is produced on the basis of the terrestrial and the aquatic ecotope map and the physiotope map (Figure 7.13). The aquatic ecotope map is the product of among others the land cover/vegetation map and the physiotope map. The aquatic ecotopes map is based on the drainage network, the location of lakes and the geomorphologic map (types).

The total of external settings in a case is called a scenario. A scenario is based on a case. To calculate a scenario, Esri grid sources (Parameter data) must be related to the necessary attributes which are not yet connected. The unconnected system attributes in the dependency scheme as defined in the case have to be connected to scenario specific sources. The results are presented in section 7.3. The parameters used are:
Parameter1: Maximum flooded area as a mask
Parameter2: Flooding frequency 9months/year)
Parameter3: Classification of the vegetation height
Parameter4: Groundwater presence based on external SIMGRO model (Jonker 2004) model

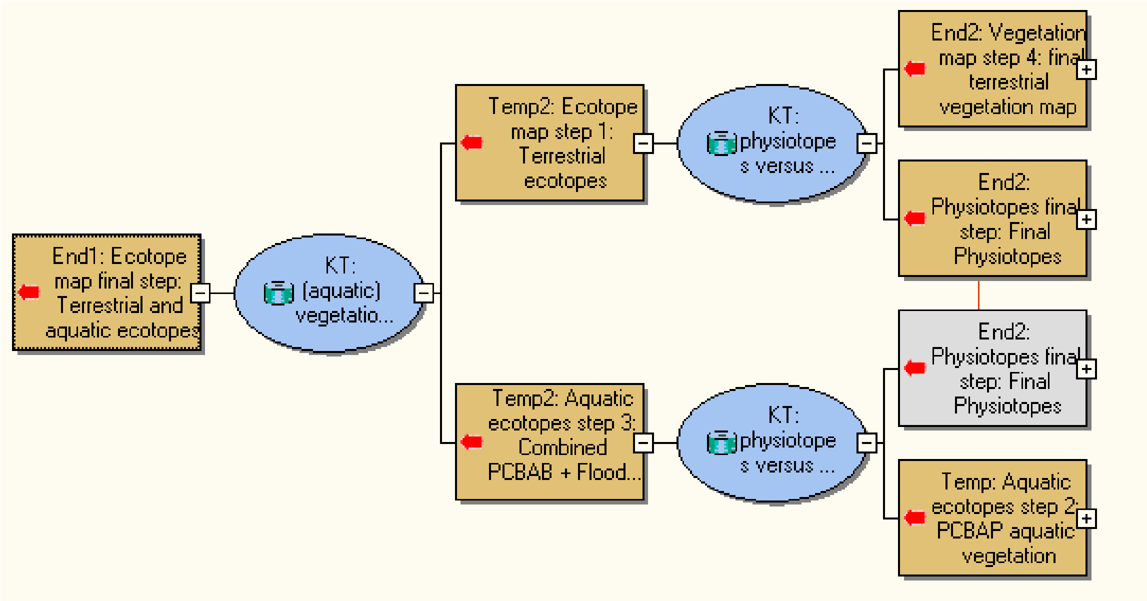
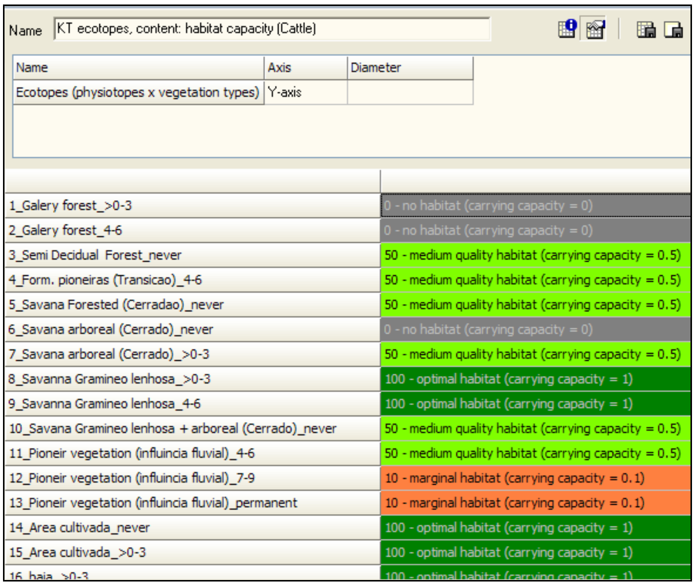


Figure 7.13 Case for final ecotope map

Scenarios in LEDESS Pantanal are based on variations in flooding frequency. The goal is to calculate the impact on biodiversity and on land use. The habitat quality for different species both cattle and wild species have been used for calculation of the impact of flooding and land use change (Figure 7.14). The scenarios calculated are:

- Current situation scenario
- Permanent flooding (more wet) scenario
- More dry scenario
- Combinations/measures like closing avulsions



Name: KT ecotopes, content: habitat capacity (Cattle)

Name	Axis	Diameter
Ecotopes (physiotopes x vegetation types)	Y-axis	

1_Galery forest_>0-3	0 - no habitat (carrying capacity = 0)
2_Galery forest_4-6	0 - no habitat (carrying capacity = 0)
3_Semi Decidual Forest_never	50 - medium quality habitat (carrying capacity = 0.5)
4_Form. pioneiras (Transicao)_4-6	50 - medium quality habitat (carrying capacity = 0.5)
5_Savana Forested (Cerradao)_never	50 - medium quality habitat (carrying capacity = 0.5)
6_Savana arboreal (Cerrado)_never	0 - no habitat (carrying capacity = 0)
7_Savana arboreal (Cerrado)_>0-3	50 - medium quality habitat (carrying capacity = 0.5)
8_Savanna Gramineo lenhosa_>0-3	100 - optimal habitat (carrying capacity = 1)
9_Savanna Gramineo lenhosa_4-6	100 - optimal habitat (carrying capacity = 1)
10_Savana Gramineo lenhosa + arboreal (Cerrado)_never	50 - medium quality habitat (carrying capacity = 0.5)
11_Pioneir vegetation (influincia fluvial)_4-6	50 - medium quality habitat (carrying capacity = 0.5)
12_Pioneir vegetation (influincia fluvial)_7-9	10 - marginal habitat (carrying capacity = 0.1)
13_Pioneir vegetation (influincia fluvial)_permanent	10 - marginal habitat (carrying capacity = 0.1)
14_Area cultivada_never	100 - optimal habitat (carrying capacity = 1)
15_Area cultivada_>0-3	100 - optimal habitat (carrying capacity = 1)
16_baia_>0-3	100 - optimal habitat (carrying capacity = 1)

Figure 7.14 Example of stored basic knowledge on habitat capacity ecotopes for cattle

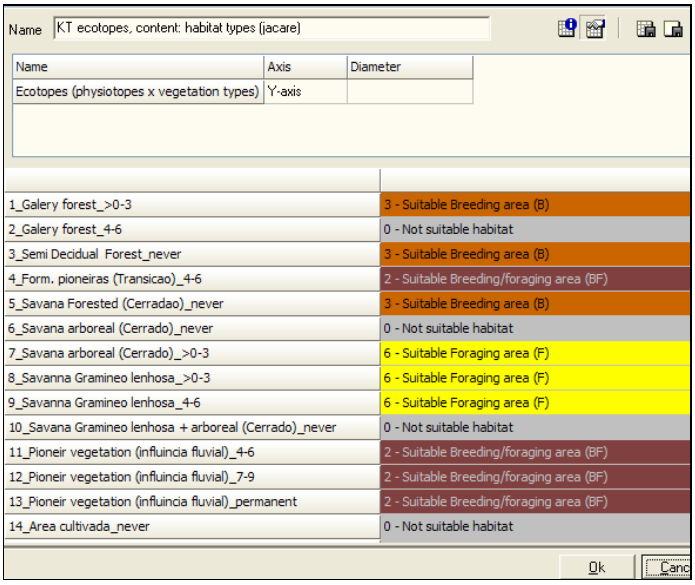


Figure 7.15 Example of stored basic knowledge on habitat types ecotopes for Jacaré

7.2.2 The LARCH model

The underlying concept of the LARCH model is the metapopulation (Box 7.I). This theory states that in fragmented landscapes, populations of animal species do not live in a continuous habitat but in a network of habitat patches, which are mutually connected by dispersal movements (Levins 1970, Andrén 1994, Hanski & Gilpin 1997). Whether a habitat network can sustain a persistent population or not, depends on:

- The characteristics of a species: habitat requirement, home range, dispersal capacity,
- The amount, shape and area of habitat patches in a landscape, connectivity of the landscape, which defines how easily species can move to other habitat patches (spatial configuration of habitat patches).

The network function of a scenario or a landscape under certain conditions can be tested on the basis of a set of "ecological profiles". An ecological profile represents a range of species with similar traits (dispersal capacity and area requirements) that can occur in a landscape (Vos et al., 2001b). Assessment of the network function of ecological profiles in a landscape is made operational in the LARCH model (Landscape Analysis and Rules for the Configuration of Habitat). LARCH is designed as an expert system, suitable for the analysis and comparison of landscape scenarios. With the LARCH model, a landscape is assessed based on a set of species or so-called "ecological profiles". Each ecological profile represents in its characteristics a group of species (e.g. "short range bird species, representative of broad-leaved forest"). A set of ecological profiles is chosen in such a way that it represents a broad range of species that can occur in the study area, differing in habitat requirement, area requirement and dispersal capacity.

Box 7.1: Concept of metapopulations and ecological networks

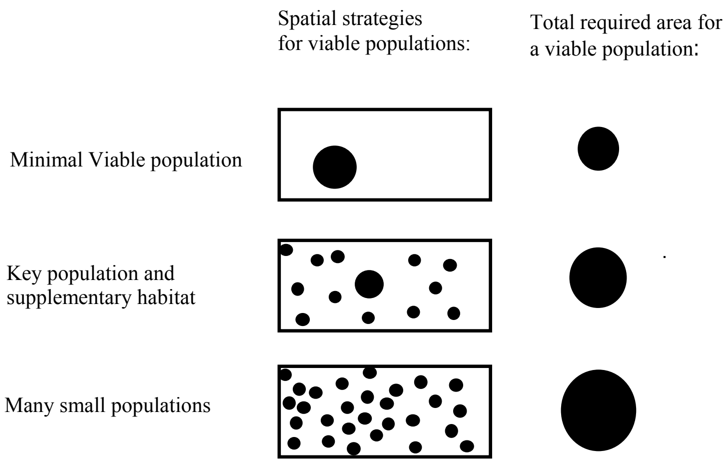
When natural habitat becomes fragmented as a result of landscape changes, small isolated patches often are too small to sustain persistent populations. These small, local populations are always at risk to go extinct, due to stochastic processes or local 'disasters' e.g. fire and pollution. When these local populations are mutually connected by dispersal movements in a habitat network, the total area of habitat patches can offer possibilities for persistent populations of species. Such a "population of populations" that can occur in a network of habitat patches is called a metapopulation.

A (meta)population can occur in different configurations in a landscape. The more the habitat of a species is fragmented, the more area is needed for a sustainable habitat network that can sustain a persistent population (figure 3).

Large populations with a very low probability of extinction, the so-called "key populations", constitute the strong parts in a metapopulation occupying a habitat network (Verboom et al. 2001). From these "key patches" a net flow of individuals to other habitat patches in a habitat network takes place. In this way in-migration can occur from a key patch to a small habitat patch where the population went extinct. If there are many habitat patches this process can result in an increased overall sustainability of the habitat network (Levins 1970, Andrén 1994). We consider a metapopulation persistent if the chance to go extinct is less than 5% in 100 years (Shaffer 1981, Verboom et al. 2001).

Standards that are used to decide whether a metapopulation is persistent or not are specific for each species. Small, short living species (for example insects) are more vulnerable and require more individuals for a persistent population than larger, long living species (like the beaver). For less mobile species habitat patches should be situated closer together to form part of a coherent habitat network. On the other hand, the area demands of e.g. insects for habitat are smaller.

Required total area for a persistent (meta)population occurring in different configurations in a landscape:



An ecological profile is built on data that express sensitivity for the fragmentation of habitat and data on dispersal capacity, habitat requirements and standards on viability of a population of the ecological profile must be available. The ecological profile depends on habitat types that occur in the study area and spatial information on habitat of the ecological profile in the study area is required. The LARCH model has been described by Chardon et al. (2000), Sluis & Chardon, (2001) and Verboom and Pouwels (2004).

Required input for LARCH is a habitat map (e.g. an ecotope map) and ecological standards or rules for the selected ecological profiles such as dispersal distance and potential density in biotope types. LARCH standards on viability are based on literature and empirical studies and simulations with a dynamic spatially structured population model, which were carried out over the past ten years (Foppen et al., 1999b; Foppen, 2001; Verboom et al., 1991, 2001, box 7.2). Since the assessment is based on potentials for a habitat network of a species, actual species distribution or abundance data are not required.

For the set of ecological profiles that are selected, the size of a (potential) key population and of a minimum viable (persistent) population is determined. The size of a population is expressed in the number of reproductive units (RU's; e.g. breeding pairs). A key population is a local population that is large enough to survive the majority of normal number fluctuations a population is faced with. The probability of extinction of a key population is less than 5% in 100 years, assuming there is at least an immigration of one individual per generation from other local populations in the same habitat network (Shaffer, 1981). If present, a key patch (a patch that can sustain a key population) forms a strong link in a habitat network. A local population that has a low chance of extinction (5% in 100 years) even without any immigration from other local populations is considered a minimum viable population (MVP).

Standards for the minimum number of reproducing individuals required in a persistent network population (probability of extinction is less than 5% in 100 years) have been derived from population dynamic modelling. These standards appear to correlate with the species group and whether or not a key population occurs in the habitat network (Verboom et al. 1997; 2001).
The configuration of habitat can be assessed with LARCH in different ways:
- LARCH-classic: Images the habitat network of an ecological profile in a landscape and assess the viability of the potential network populations;
- LARCH-SCAN: Quick-scan survey of the spatial cohesion of habitat patches in a landscape shows strong and weak parts of a habitat network.

The principles of LARCH-classic are simple. The analysis consists of two main steps: the habitat modelling and the viability analysis (Figure 7.16).

From the input map, all patches that function as the limiting habitat of an ecological profile are selected (Figure 7.16a and b). A habitat map for the ecological profile appears. The size of a habitat patch and the density of individuals that can occur in the particular type of biotope/vegetation type determine the potential number of individuals that a patch can sustain.

Habitat patches that are located near to each other allow for movement of individuals on a daily basis, the so-called home range. Such habitat patches are fused into a cluster and considered a local population (Figure 7.16b). The total size of the habitat patches within home range must meet at least a certain minimum in order to hold a territory of one reproductive unit (Fahrig, 2001). Habitat patches that, even after a fusion, are not large enough according to the species-specific standard are not further regarded as a suitable habitat site.

Based on the size of the patch and the potential density of the species in a specific type of habitat, the number of reproductive units (e.g. breeding pairs) is defined for each patch (Figure 7.16c). A population is only large enough to cope with normal fluctuations in the population, caused by stochastic events for example, if the number of the population is sufficiently large, larger than the standard for a 'minimal viable population' (MVP). In many fragmented landscapes, this is no longer a realistic option and we rather speak in terms of so-called 'key populations'. These are populations of a certain size within a network that are large enough to cope with the majority of normal fluctuations that a population is faced with. Other populations that are too small to meet these standards are identified as 'small populations' (see Box 7.1).

Habitat patches can be mutually connected, by the movement of animals from one habitat patch to another when searching for new habitat (dispersal). Patches that display a sufficient level of exchange with each other belong to the same habitat network (Figure 7.16d).

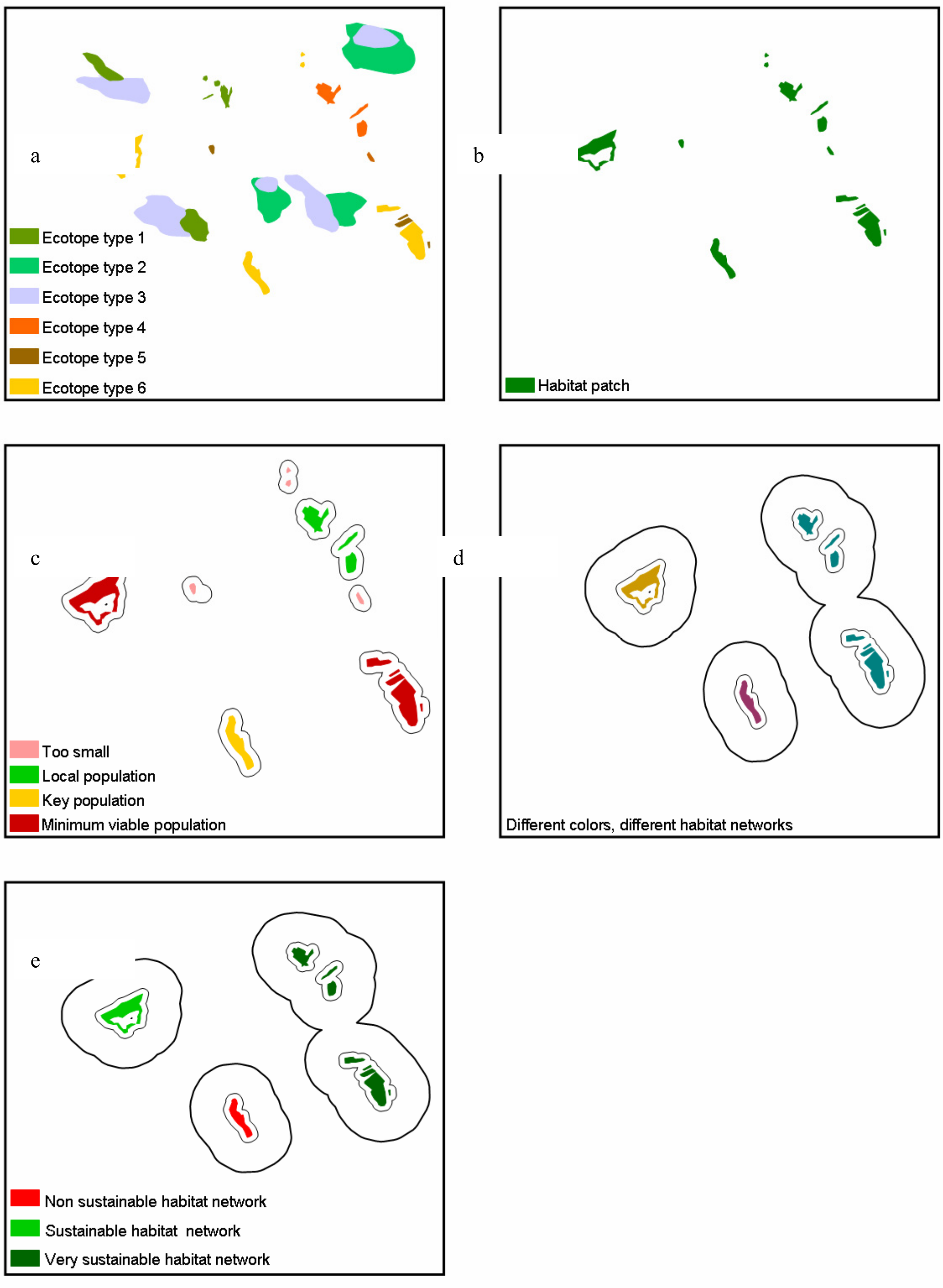


Figure 7.16 LARCH-classic habitat network assessment.

Finally, it is determined whether the habitat networks can sustain persistent populations of the ecological profiles (Figure 7.16e). The criterion used for persistent populations, that can occur in a sustainable habitat network is that the chance that the population still exists in an area after 100 years is greater than 95% (Shaffer 1981, Verboom et al. 1997). It is assumed that the area does not undergo any changes, or only slight changes, during this period of time. Standards that are used are shown in Table 7.3. These standards are derived from population dynamic modelling.
The LARCH-SCAN module provides insight in the spatial cohesion of habitat patches and shows the strong and vulnerable elements of a habitat network. Both the area of a habitat patch as the connectivity with other habitat patches are of importance for the spatial cohesion of a habitat patch of a specific species (Verboom et al. 1991; Hanski, 1994).

Table 7.3 Standards for viability of populations (Verboom et al. 2001). RU = Reproductive Unit.

	Key population	Viable population including key population (RU	Viable population without key population (RU)	Minimal Viable Population (RU)
medium mammal	40	120	200	60
large mammal	20	80	120	30
large bird	20	80	120	30
medium reptile	40	120	200	60
large reptile	20	80	120	30

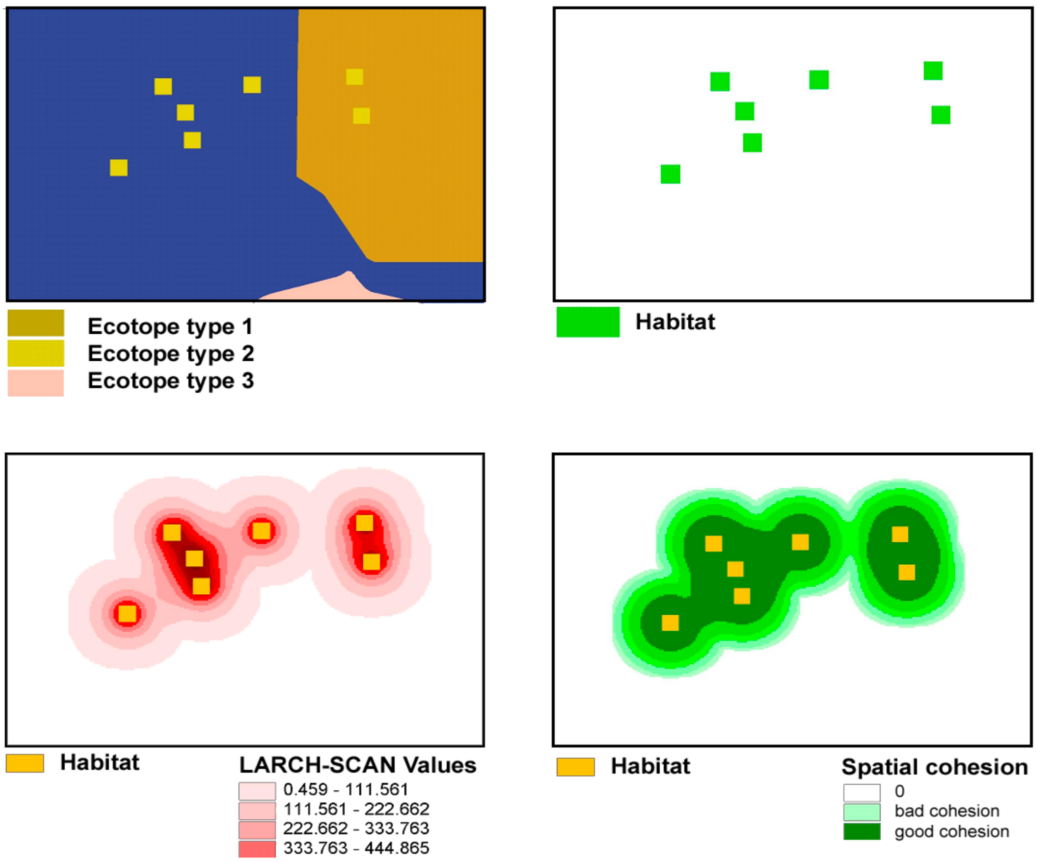


Figure 7.17 LARCH-SCAN habitat network analyses. Based on habitat present the spatial cohesion is calculated (shown in the graduated colour). See annex III for the algorithm used.

The required input for LARCH-SCAN is a grid map that provides information on the habitat characteristics and ecological profiles. LARCH-SCAN determines the spatial cohesion of habitat, using the calculated connectivity of habitat grid cells. The connectivity value of a grid cell depends upon the amount of and distance from surrounding suitable

habitat grid cells. The contribution of each habitat patch or grid cell to the connectivity is inversely proportional to the distance. Because the method examines each individual grid cell, the degree of connectivity between habitat patches is considered as well as the surface areas of the habitat patches themselves.

The next step involves the determination of the threshold values for the degree of spatial cohesion, which can be defined as a function based on carrying capacity (or potential density of a species), the minimum and maximum calculated values and dispersal distance. The image thus created, a 'spatial cohesion map', provides insight into the degree that habitat areas are connected, and the weak and strong parts of a habitat network (Figure 7.17). It gives also insight in the potential of an area to function as a corridor for species. River regions in particular are very suitable for functioning as a corridor (Foppen et al. 1999a; Pedroli 1999, Sluis & Chardon, 2001; Rooij et al., 2000). This is obvious for aquatic organisms, such as fish, but certainly important for birds and mammals as well.

The LEDESS and LARCH model are par excellence suited for comparing the effects that can be expected in different scenarios. These scenarios should be described in terms of the determining factors of the ecotopes that are modelled and data that have to be taken into account in the modelling, e.g. map of barriers.

In this study, the determining factors for ecotopes and available data were compiled a workshop with experts on fauna and vegetation of the Pantanal. The scenarios assessed were defined on the preliminary study, on the results of the stakeholder workshop in 2003 in Corumbá and further analysis by the research consortium. It takes into account:

- The expert knowledge on ecotopes;
- The available digital spatial data of the study area;
- The potential effective measures for influencing the flooding regime in the area based on regional and research expertise;
- Autonomous developments in the area that can influence the biodiversity.

Species can need several types of habitat to complete their life cycle, for example foraging habitat, breeding habitat and resting habitat. In modelling species focus is on the most limiting habitat type (often breeding habitat) assume that other habitat types are sufficiently available and accessible in the near surrounding area.

The selection of species that are modelled in a study is an important choice in the process. The species that should be selected should obligatory comply with a number of criteria. The species should obligatory:

- Represent a range of species with similar dispersal capacities and area requirements for viable populations (the species should not have very exceptional characteristics)

- Be associated with a specific type of habitat that can be spatially delineated and that responds to expected changes in inundation (i.e. disappearing of forest, different allocation of wetlands).

And preferably:

- Is a protected species
- Is an appealing species
- Represents different kinds of functional groups (birds, mammals etc.).

With a well-chosen set of ecoprofiles the effects of changes in a landscape can be expressed in the effects on the viability of different species (biodiversity). A suitable set of ecoprofiles should meet the following criteria:
The set of ecoprofiles contains species that represent different scale levels (have different dispersal capacity: e.g. 5 – 30 – 75km);
The set of ecoprofiles contains species with a different area requirements for viable populations

7.2.3 Fish ecology

From 1979 to 1983 the amount of fish caught in Taquari river basin ranged from 300 – 620 ton per year according to EMBRAPA data (Table 7.4). Since 1994 fish catch was less than 100 ton per year and is about 5-6% of the catches in the whole Pantanal in Mato Grosso do Sul, although it is one of the largest river basins. From this we can conclude that the stock size has declined and is below the average.

The hypothesis, which might have caused this, is the flood pulse concept. The Flood Pulse Concept (Junk et al 1989) states that the pulsing of the river discharge that extends the river into the floodplain is the major force controlling biota in rivers with floodplains. The flood pulses control biota in three ways: directly by (1) facilitating migration of animals, indirectly by (2) enhancing primary production in the floodplain and by (3) habitat structuring. The floodplains provide important factors for driving ecological processes in the riverine ecosystem. During floods biota migrate both actively and passively between different habitats in the river floodplain system, where they feed (Wantzen et al 2001). The lateral exchanges between main channel and floodplain, and nutrient recycling within the floodplain has according to Grift (2001) more direct impact on biota than by the processes described in the River Continuum Concept. Fish move along their corridor in different speed and with different steps. The strong interaction between the river and the riparian ecosystems in its ecotone provide a huge exchange of energy, matter and nutrients. Networks of river corridors maintain the genetic exchange between populations in natural and impacted landscapes.

Table 7.4 Fish catches in kg in the period 1995 to 2000 in the Rio Taquari and totals of the Rio Miranda and Mato Grosso do Sul. The year 2000 was a year with low catches in nearly all rivers (Catella et al, 1998, Catella and Fernandes de Albuquerque, 1999, 2000, Catella et al 2001, 2002, Campos et al 2002)

year	Professional catches	Sport fishing catches	total	Rio Miranda total	Mato Grosso do Sul Total
1995	5.254	61.817	67.071	251.848	1.269.431
1996	1.733	48.780	50.513	348.268	1.225.049
1997	13.448	45.632	59.080	363.913	1.453.383
1998	17.902	59.025	76.927	411.117	1.429.653
1999	11.539	67.471	78.010	375.126	1.411.478
2000	4.204	43.887	48.091	179.451	795.987

In the Pantanal there are two different types of migrating species. Longitudinal migrating fish move upstream and downstream the river. They breed in the small rivers of the Planalto and feed downstream, in the rivers and floodplains in the period February to July. When the water level decreases in August/September they return to the river channel and if they are adult they swim upstream for spawning. Lateral migrating fish have their pathway from the river to the floodplains. During February to April they spawn eggs and larvae in the floodplain. In the dry season they go to the river.

Because of sedimentation in the Taquari basin the river bed is very shallow. In the past, before 1960 the floodplains became dry in the dry period and flooded during the wet season. With this flooding nutrients are introduced into the floodplain grasslands and forests, which was the feeding ground of small plant eating and detritivorous fish.

Due to sedimentation there is a lack of flood pulse in the Taquari river basin. Figure 7.19 shows a cross section of the river bed before (above) and after sedimentation (under). After sedimentation large areas are flooded permanently. This results in decay of forests and macrophytes and a decline in nutrients. This also might have caused a decrease in the amount of detritus in the floodplain. Therefore, the number of detritivorous fish declined. In addition, fish feeding on fruit, flowers and part of plants have decreased. The macrophytes become less suitable habitat for aquatic insects, perifiton and perizoon, resulting in less food for detritivorous, herbivorous and insectivorous fish. Sedimentation also causes shifts in the corixos, the side channels and in the main river channel, which might result in barriers for migrating fishes. The restriction in movements will have a direct impact on the breeding success, survival of young and feeding. This is probably expressed in the catches in the river.

Box 6.2
Longitudinal migratory piscivorous fish
Key species: Pintado
Group: Cachara, Dourado, Jau, Barbado, Jurupoca, Jurupesen.
They feed on fish and migrate between the Planalto and the floodplains. In the dry season the adult fishes migrate to the rivers in the planalto to reproduce. When the water rises the eggs, larves and adults flow with the river to downstream areas. There they forage in every water body that is connected to the river. The water can be shallow. If the water level decreases after the wet season they go back to the river and swim upstream to the planalto. From this we can conclude the need for connection between flooded habitats and the river channel.

Longitudinal migratory omnivorous fish
Key species: Pacu, *Piaractus mesopotamicus*
Group: Pitaputanga
This group also migrates upstream to the planalto for reproduction and downstream to the floodplain for feeding. In the floodplain they feed on animals, (especially) fruit, seeds, flowers and insects from the riparian vegetation and flooded pioneer and cerrado vegetation. Because of permanent flooding, some of these forests died resulting in a loss of their feeding habitat.

Longitudinal migratory detritivorous fish
Key species: Curimbata, *Prochilodus lineatus*
Group: *Potamorhina squamoralevis*
This longitudinal migration group feeds on detritus (decomposed organic matter), periphyton and perizoon coming from the temporary flooded terrestrial vegetation. The optimal habitat is in slow flowing shallow flooded vegetation (water depth < 1 m). Due to their migrating characteristic their feeding habitat has to be connected to the river.

Floodplain spawners piscivorous fish
Key species: Piranha, *Pygocentrus nattereri*
Group: Dourado cachorro, Traira, Serrasalmus marginatus, Serrasalmus spilopleura, Pygocentrus natterei, Roeboides paranensis, Roeboides prognathus, Charax gibbosus, Acestrorhynchus pantaneiro, Hoplias malabaricus
The floodplain spawners lay their eggs and larves in the floodplain. In the dry season they stay in lakes and some of them go to the main river channel. They feed in slow streaming/standing water which is connected to the river.

Floodplain spawners detritivorous fish
Key species: Sairu, family Curimatidae
Group: Curimatopsis myersi, Curimatella dorsalis, Psectrogaster curviventris, Cyphocharox gillii
The group of the Sairu feeds on detritus and has an optimal habitat in the connected lakes, oxbow lakes, corixos and flooded Savanna Gramineo lenhosa and pioneer vegetation.

Due to sedimentation there is a lack of flood pulse in the Taquari river basin. Figure 7.19 shows a cross section of the river bed before (above) and after sedimentation (under). After sedimentation large areas are flooded permanently. This results in decay of forests and macrophytes and a decline in nutrients. This also might have caused a decrease in the amount of detritus in the floodplain. Therefore, the number of detritivorous fish declined. In addition, fish feeding on fruit, flowers and part of plants have decreased. The macrophytes become less suitable habitat for aquatic insects, perifiton and perizoon, resulting in less food for detritivorous, herbivorous and insectivorous fish. Sedimentation also causes shifts in the corixos, the side channels and the main river channel. This might result in barriers for migrating fishes. The restriction in migration will have a direct impact on the breeding success and survival of young. This is probably expressed in the catches in the river.

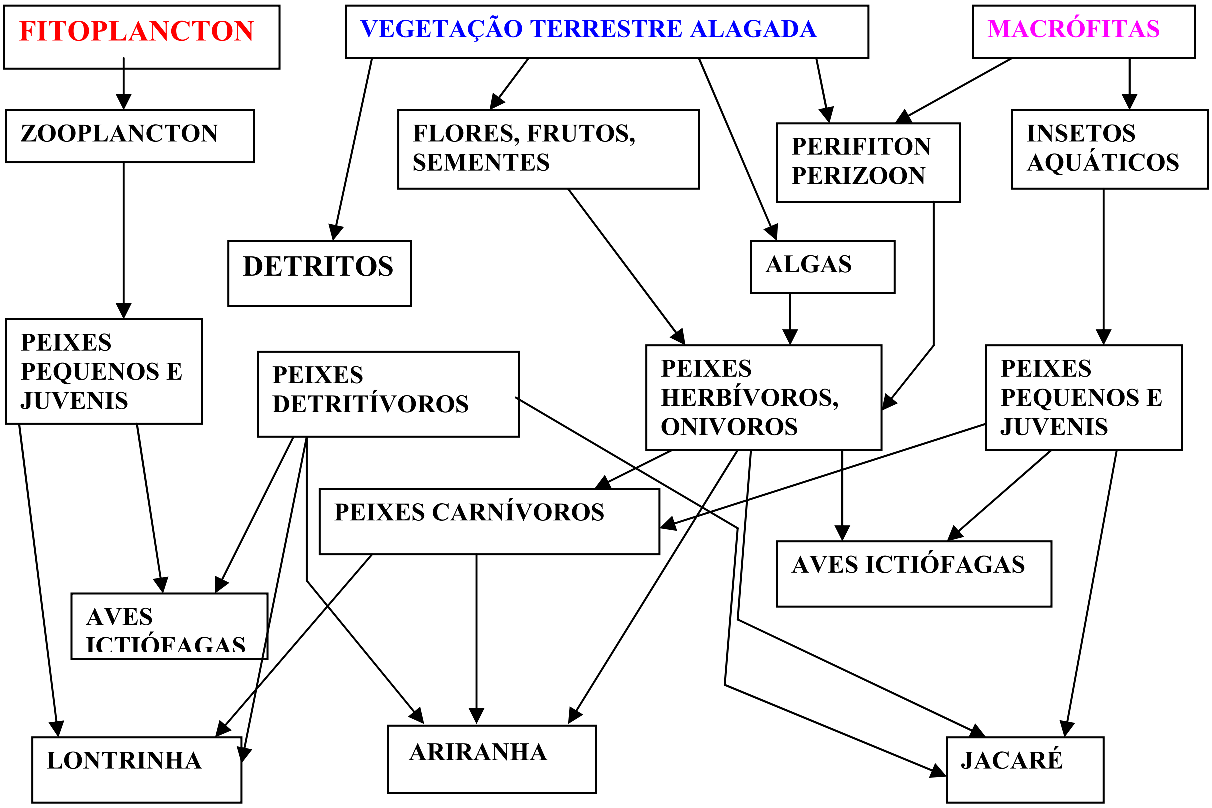


Figure 7.18 Food network in the Pantanal wetlands (E. Kawakami de Resende)

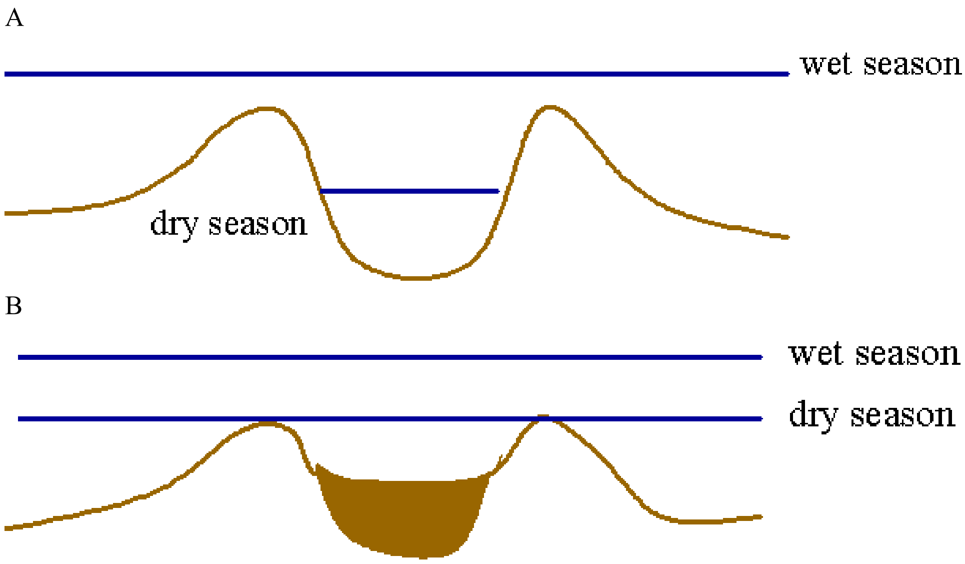


Figure 7.19 The differences in water level in rivers that probably cause decline in fish population. A before excessive sedimentation, B, after sedimentation the floodplains are permanently flooded (E. Kawakami de Resende).

Based on these considerations five groups of fish species have been made on their feeding and migration characteristics:
1 Longitudinal migrating piscivorous fish
2 Longitudinal migrating omnivorous fish:
3 Longitudinal migrating detritivorous fish
4 Floodplain spawners piscivorous fish
5 Floodplain spawners, detritivorous fish
The groups are described in Box 7.2. Insectivorous fish is a separate group that is important, but not further considered to include in the evaluation.

Longitudinal migrating fish can swim around 400 to 600km. Network dispersion distance for most fishes is estimated at 2–3km. However, data o migration and the duration of stay are not known yet. These are important parameters for estimating population dynamics and reaction on the pat changes.

In the Pantanal the following different aquatic habitats have been determined with characteristics as presented in Table 7.5.

Table 7.5 Characteristics of water biotopes that are important fish habitat parameters.

	Velocity of water flow	Water depth	Availability of aquatic habitat	Vegetation
River/Rio	Fast	Deep	Permanent	+/-
Linked Baía	Fast	Shallow	Permanent	+/-
Oxbow	Standing	Deep	Permanent	+
Isolated Baía	Standing	Shallow	Permanent	+/-
Vazante	Moderate	Shallow	seasonal	+
Corixo	moderate	Shallow/medium	seasonal	+
Flooded riparian vegetation	Moderate to standing	Shallow	seasonal	+
Pioneer vegetation and grass savannah	Moderate to standing	Shallow	seasonal	+

The habitat characteristics as water depth, flow velocity and the periodicity of the habitat cannot be translated yet in map characteristics in the maps at present available. That means that for fish no scenarios can be developed yet. What has been done is development of ecoprofiles for fish and the inclusion of the aquatic habitats in the ecotope map. However scale and precision of the categories do not allow further calculation of scenarios. For this kind of analysis more and precise spatial data are required.

7.3 Results

7.3.1 LEDESS-scenarios and Larch modelling parameters

For the scenario development, a time horizon of more or less 50 years is used. In some decades, major changes in the study area can occur. The scenarios that are assessed with LEDESS and LARCH are formulated, taking into account the autonomous developments in basin of the Taquari river, such as climate variability, the geological development of the fan and the continuous sedimentation as well as proposed measures as formulated in the first stakeholder workshop. These were:

- Drainage of the Taquari
- Closing of the Caronal Avulsion
- Prevent new avulsions
- Help the rive to create new river channel from the Caronal to the west
- Construction of dikes
- Construction of a dam
- Prevention of erosion by planting Forest along rivers on the Planalto
- Prevention of erosion by capacity building on erosion and river management
- 'Doing nothing' but buy out the inundated land and make it a national Park.

The final scenarios that are formulated are:

"Present situation":	The average situation of the Taquari floodplain area at present based on Landsat 1998 interpretation of flooded areas. It is a picture of this moment that can change due to sedimentation, changes in discharge and impact of man.
"Wet scenario":	This situation that reflects the situation when more discharge (20%) is entering the area resulting in longer flooding periods. Also, this scenario can be interpreted in a different way, for small areas; as a result of local measures in the river, locally areas can get flooded more often. This scenario is based on LANDSAT images of 1998 with maximum flooding (Table 1.1, 1.2). This also reflects the situation of further sedimentation in the cone of the Taquari fan causing more inundation.
"Dry scenario":	This situation that reflects the situation when less water is entering the study area. Also, this scenario can be interpreted in a different way, for small areas; as a result of local measures in the river, making areas flooded less often or flooded selectively. In the "dry scenario", the effect of less flooding can be looked up on the specific location where you expected these dryer circumstances. This scenario is based on the interpretation of LANDSAT 1998 that it reflects the dry period of the early 1970s (Table 1.1, 1.2). This reflects also situations of longer dry periods that might occur in future due to climatic variations.

Closing Caronal avulsion"	This scenario contains one of the measures that can be taken to influence the flooding pattern of the Taquari river and that has been proposed by the stakeholders. With LEDESS the effects on the distribution of ecotopes is assessed. The effects on biodiversity at of the fauna, however, were not assessed.

In the LEDESS Pantanal modelling the major flooding parameters that have been used are:
- Parameter1: Maximum flooded area as a mask
- Parameter2: Flooding frequency 9months/year)
- Parameter3: Classification of the vegetation height
- Parameter4: Amount and flow of groundwater modelled with external SIMGRO model (Chapter 6)

In the workshop of March 2004 species have been selected for modelling (Table 7.6). This selection was largely based on the availability of knowledge on the field behaviour of the species. A selection is used to illustrate the effects of the scenarios on the distribution and viability of populations. Cattle have been included as well and this reflects the changes in area available for cattle breeding. The other selected species illustrate relevant effects on biodiversity and showed the most reliable modelling results.

In the March 2004 workshop in Corumbá, species specialists of the Pantanal have elaborated the required spatial characteristics of these species and made expert based estimates of the carrying capacity of the ecotopes for these species. The results of this workshop have been elaborated in scaling of the different habitats in their suitability for the species. The data are available at EMBRAPA-Pantanal and at Alterra. An overview of predominant habitat for different species is presented in Table 7.7.. The results are summarised in dispersal capacity and ecotope suitability. These species are used further in modelling. This overview shows that a large range of ecotope groups are used by the species and that the landscape is utilised at various scale levels (variation in dispersal capacity).

Table 7.6 Selection of species in the workshop of March 2004. Bold: species that are used for illustrating the effects on biodiversity.

English name	Portuguese name	Scientific name	Species group
Red brocket deer	Veado-mateiro	*Mazama americana*	medium mammal
White-lipped peccary	Queixada	*Tayassu pecari*	medium mammal
Jabiru stork	Tuiuiú	*Jabiru mycteria*	large bird
Paraguayan caiman	Jacaré	*Caiman crocodilus yacare*	medium reptile
Marsh deer	Cervo-do-Pantanal	*Blastocerus dichotomus*	medium mammal
Pampas deer	Veado-campeiro	*Ozotoceros bezoarticus*	medium mammal
Greater rhea	Ema	*Rhea americana*	large bird
Giant anteater	Tamanduá-bandeira	*Myrmecophaga tridactyla*	large mammal
Cattle	Gado	*Bos spp*	large mammal
Giant otter	Ariranha	*Pteronura brasiliensis*	large mammal
Jaguar	Onça pintada	*Panthera onca*	large mammal
Yellow anaconda	Sucuri	*Eunectes notaeus*	large reptile

Table 7.7 Overview on characteristics of selection of species. Small dispersal capacity = +/- 0-5 km; Medium dispersal capacity = +/- 10- 40 km; Large dispersal capacity = +/- 50 and more km

Ecotope groups	Dispersal capacity		
	small	medium	large
Forest		white lipped peccary red brocked deer	jaguar
pioneer vegetation		marsh deer	jaguar
vazante	ema	marsh deer	
baia			cattle
savanna	ema	pampas deer	cattle
cultivated area			cattle

7.3.2 LEDESS Scenario results

The results of the LEDESS-Pantanal scenario analysis is given for the scenarios presented above. The results show considerable variation in flooding of the alluvial fan.

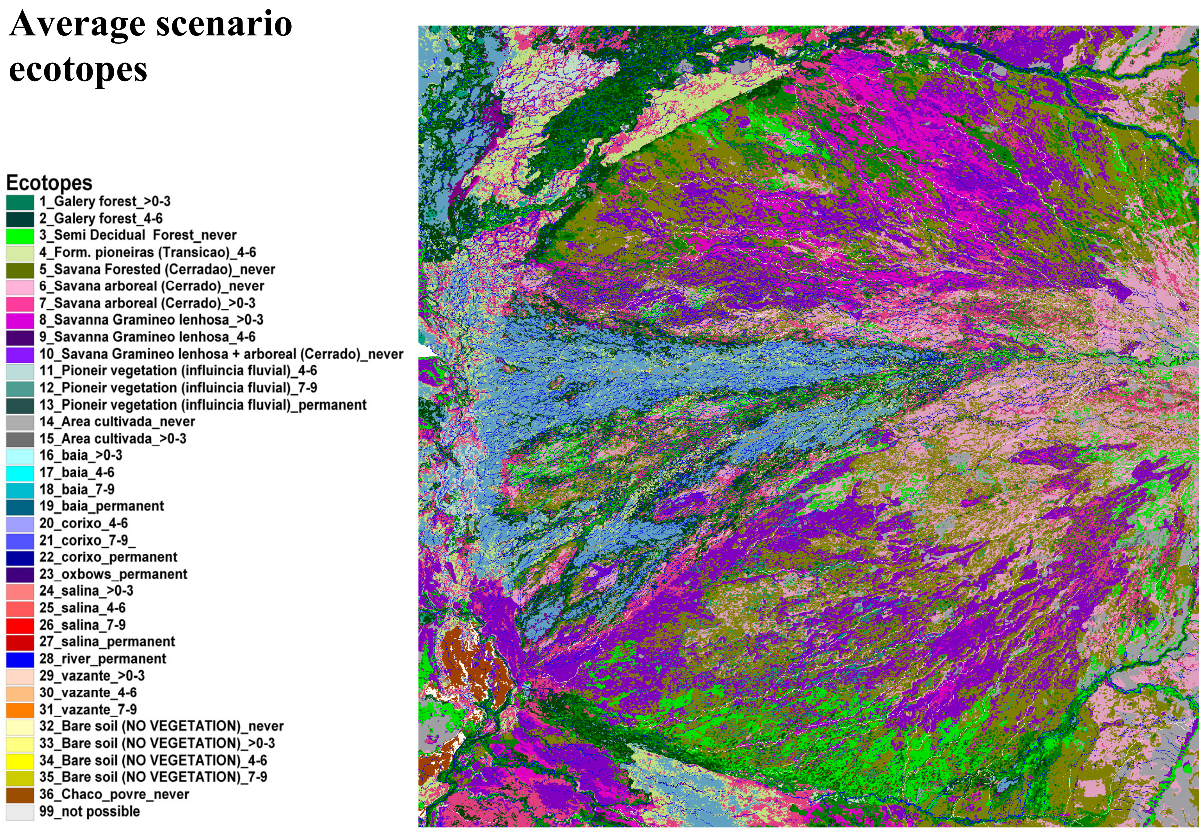


Figure 7.20 Ecotope distribution in the average scenario

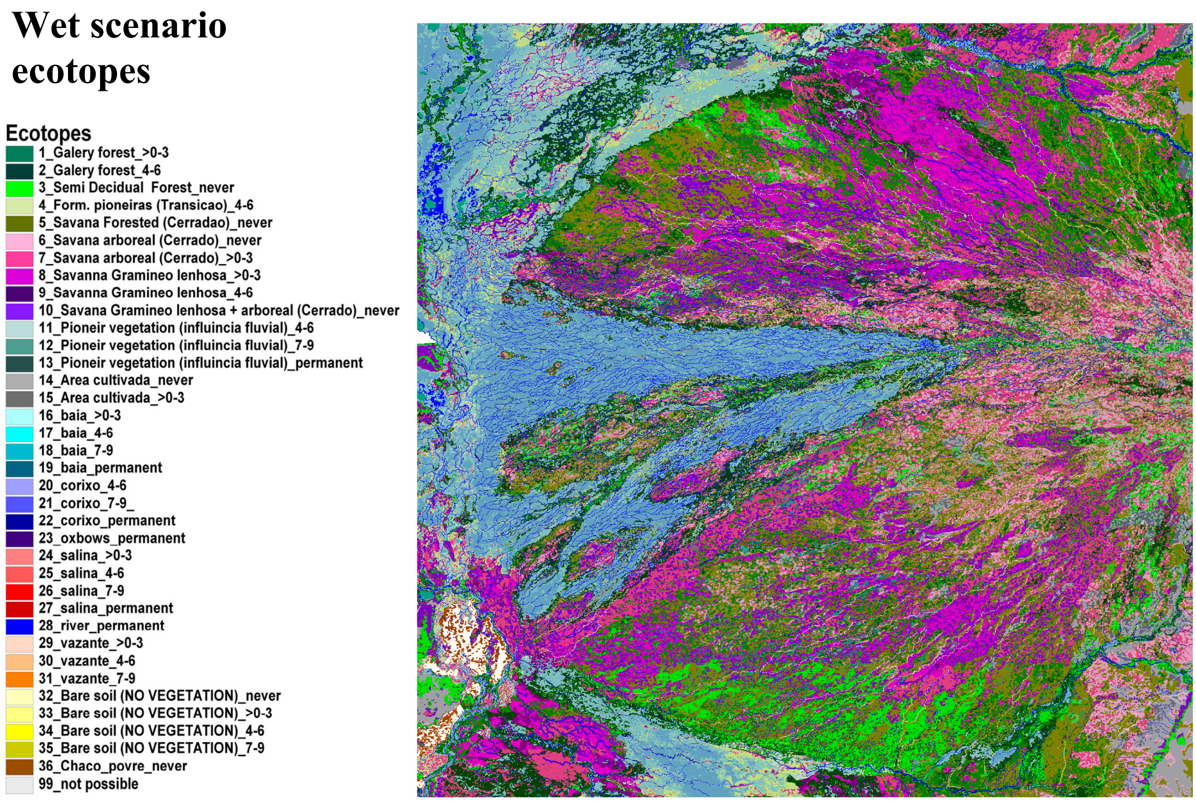


Figure 7.21 Ecotope distribution in the wet scenario

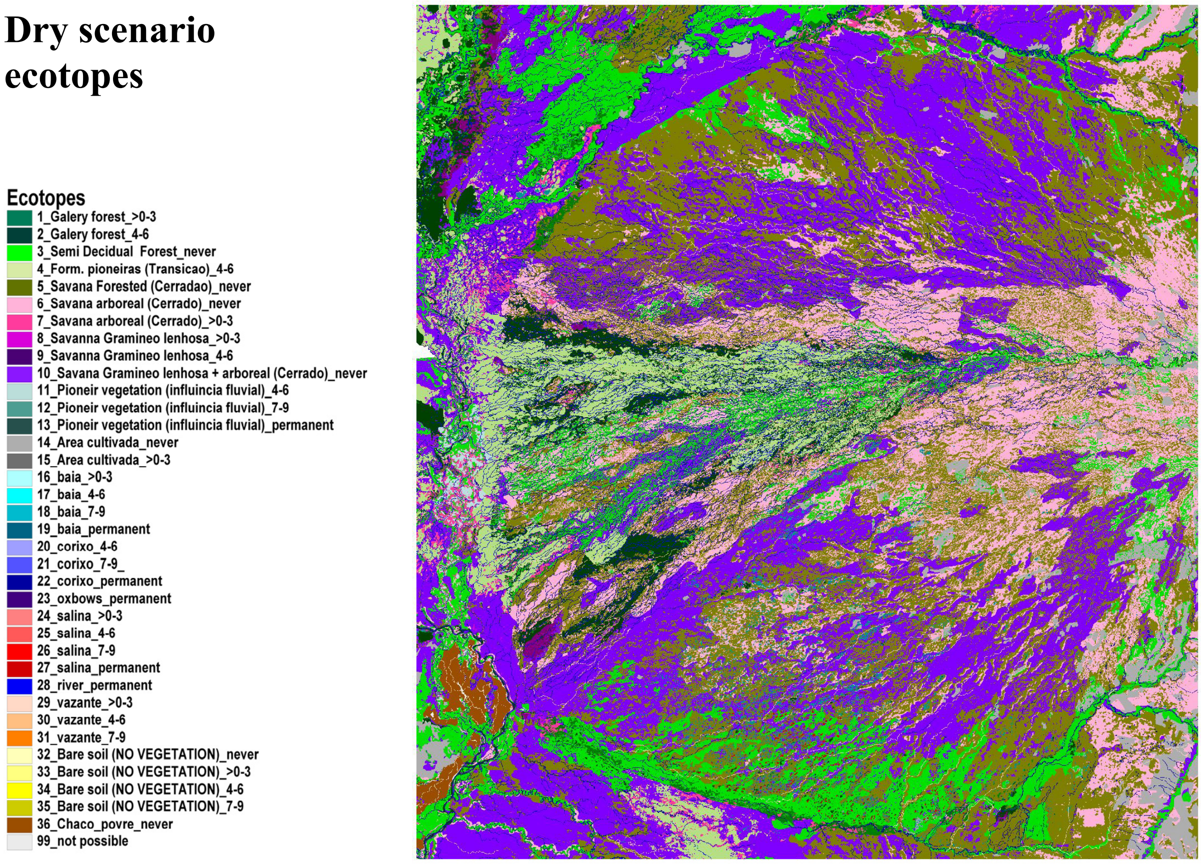


Figure 7.22 Ecotope distribution in the dry scenario

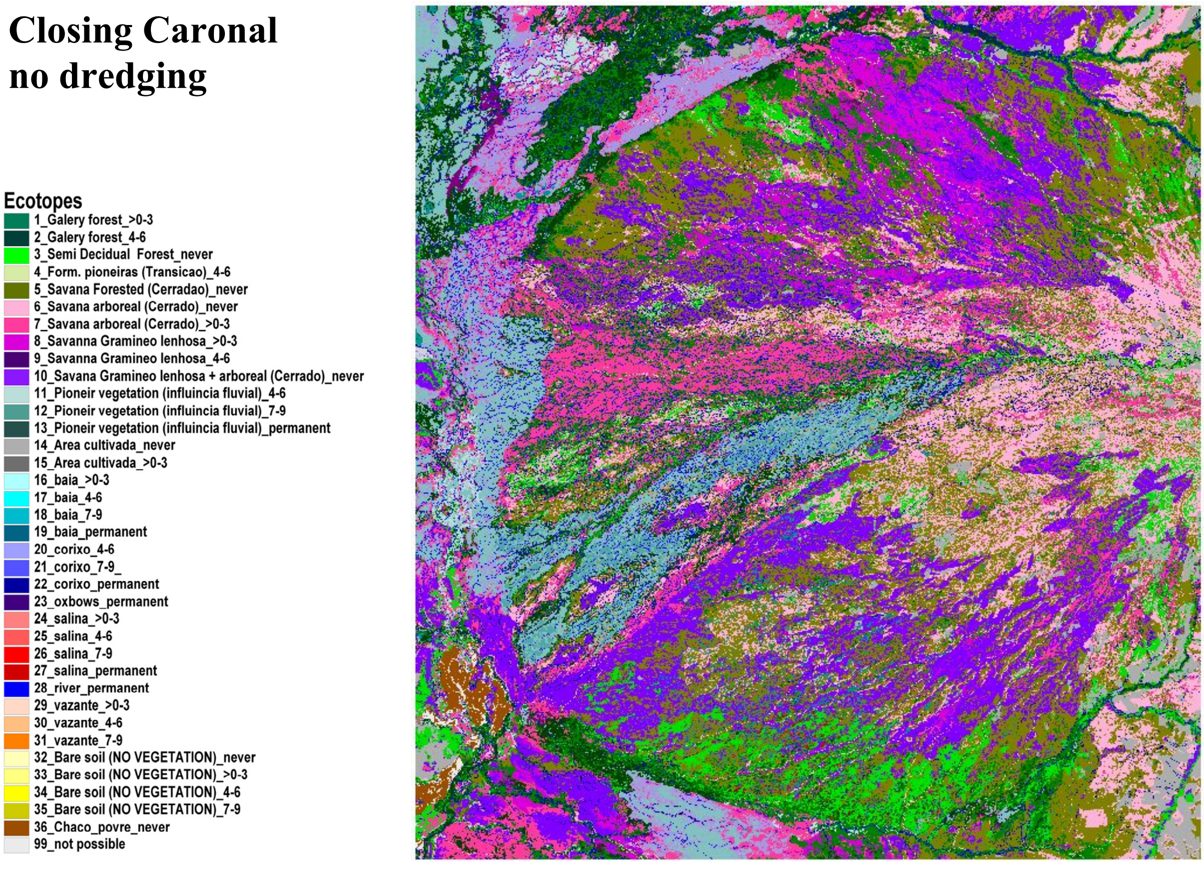


Figure 7.23 Ecotope distribution in the Scenario of the closing of the Caronal Avulsion

The most important differences between the present situation and a wetter and dryer scenario occur in the Caronal avulsion (Figure 7.24), along the present Taquari river bed and along the Paraguai River in the north. If there is more discharge the flooding will increase considerably. Flooding along the Paraguai will be caused by changes in the Bacia do Alto Paraguai that is not considered further in this study. More discharge or more sedimentation and therefore less storage in the present bed of the river will increase the flooding both in the Caronal avulsion and along the present river, supposing that it still will remain a discharge channel.

In dryer situations forest will increase, mainly cerrado and cerradão (high cerrado) and the river related vegetation will decline.

In the situation that the Caronal avulsion is closed (Figure 7.23), the area behind the avulsion gets dryer. However, due to the restricted discharge capacity in the present channel of the Taquari it will cause an increased flooding along the Taquari. If no additional measures are taken the flooding will just be reallocated

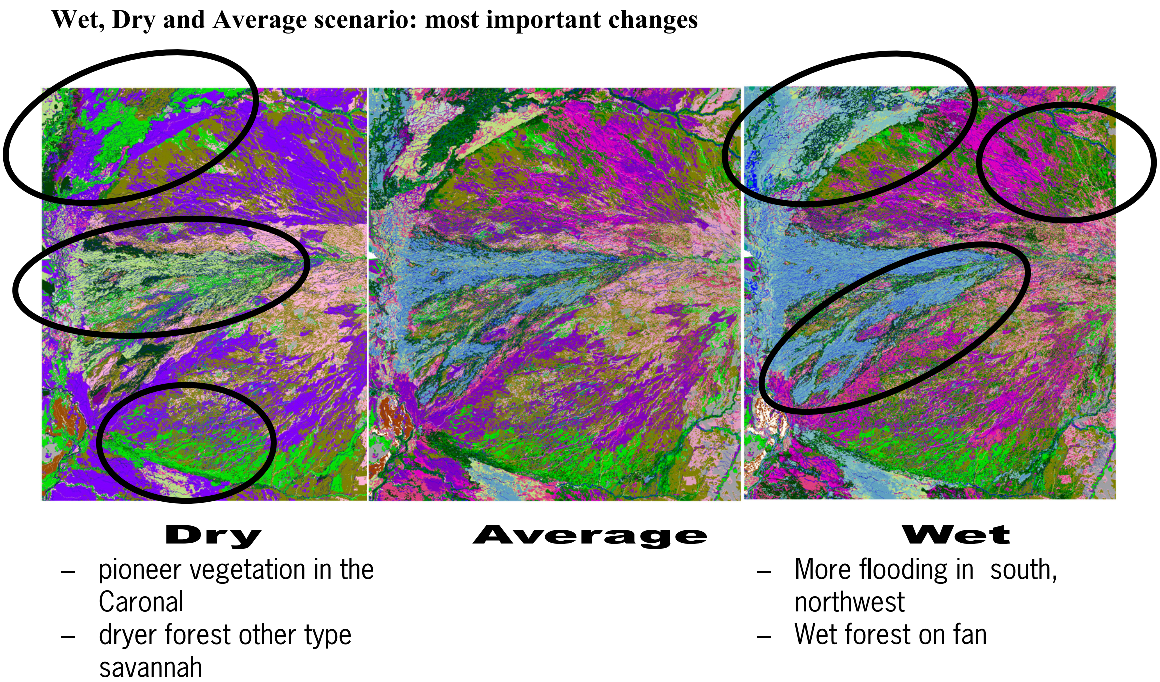


Figure 7.24 Area with major differences between the average, wet and dry scenario.

Distribution of the ecotopes and their abundance changes considerably between the different scenarios. In the wet scenario the permanent flooded are increases considerably as does the area of pioneer vegetation. In general the forested areas decline and are replaced by flooded areas and pioneer situations. In the situation that the fan gets dryer, the cerrado related ecotope types such as cerrado forest and forested savannah (Figure 7.25).

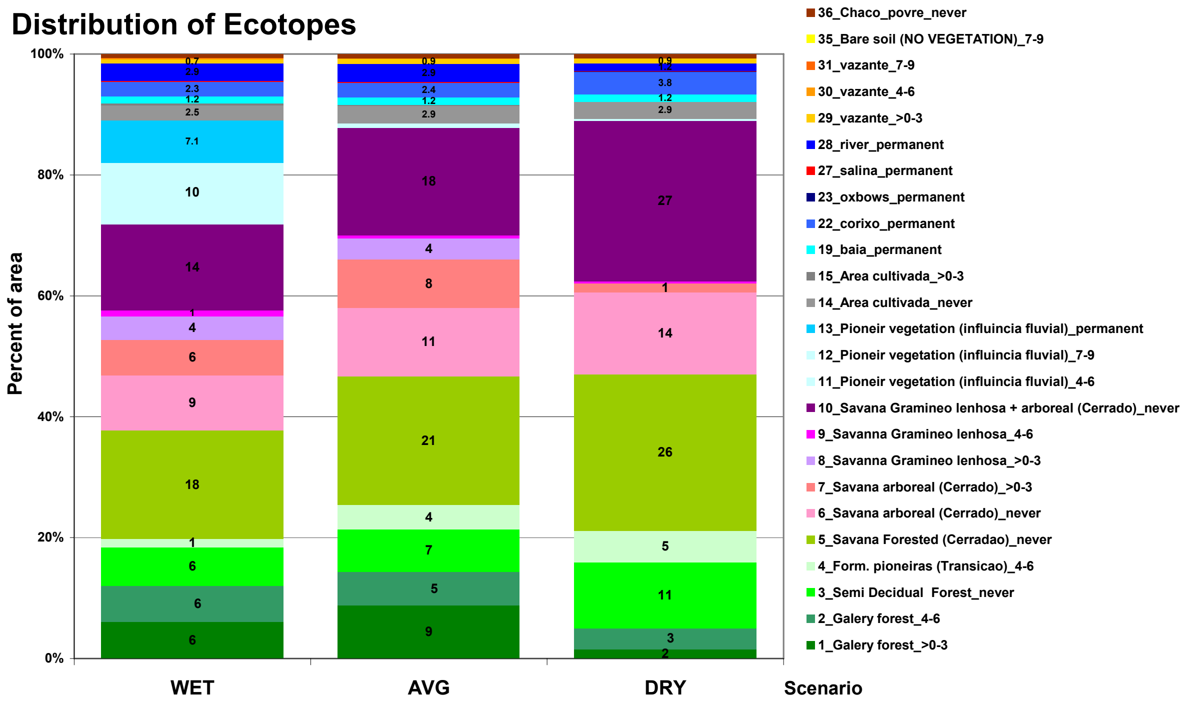


Figure 7.25 Percentage cover of the ecotope types in the different scenarios.

7.3.3 LARCH-SCAN Modelling results

The cohesion of habitat of the species in the present situation is calculated with LARCH-SCAN. The results are shown in Figure 7.26 to 7.32. The resulting cohesion is calculated on the basis of the amount of suitable habitat on a site area and in the surrounding area. The habitat that is within dispersal distance of the species assessed is taken into account. A dark colour in the figures show areas where many coherent habitat patches are present and the pale colours indicate little and/or isolated habitat areas. The most sustainable populations can be expected in the dark coloured areas. Also the degree isolation of populations can be derived from these LARCH-SCAN figures.

For species that are confined to the wetter parts of the area, as Marsh deer and Jaguar, three main areas where relatively strong populations occur appear. The habitat within these cores areas are far better connected for species as the Jaguar than for species as the Marsh deer, because of their larger dispersal capacity (Figure 7.27 and Figure 7.28). The central core area appears to be the most stable one. For species as the Marsh deer, the southern core area appears isolated. The north core area appears to be poorly connected with the central core area. Changes in the flooding regime can result in a better or worse cohesion of these core areas.

For the species that are more confined to the dryer and more open parts in the Taquari area as Greater rhea and Pampas deer, the habitat is coherent. The part north of the Taquari river, however, is better suited than the part south of this river. The wet area along the Taquari river can be a barrier between the northern and southern habitat areas: this area

constitutes a weak link that can easily be broken by the loss of habitat along the Taquari river. Further, in the relatively dry centre between the lower Taquari branches, the populations of species as Greater rhea and pampas dear are relatively isolated.
The centre of gravity of populations of species as Red brocket deer and White lipped peccary, with a habitat in more forested dry parts of the wetland is mainly situated south of the Taquari river. And isolation is no problem at present. The habitat of White-lipped peccary is more coherent than of Red brocket deer due to the larger dispersal capacity of the White-lipped peccary (respectively. 25 km and 10 km).

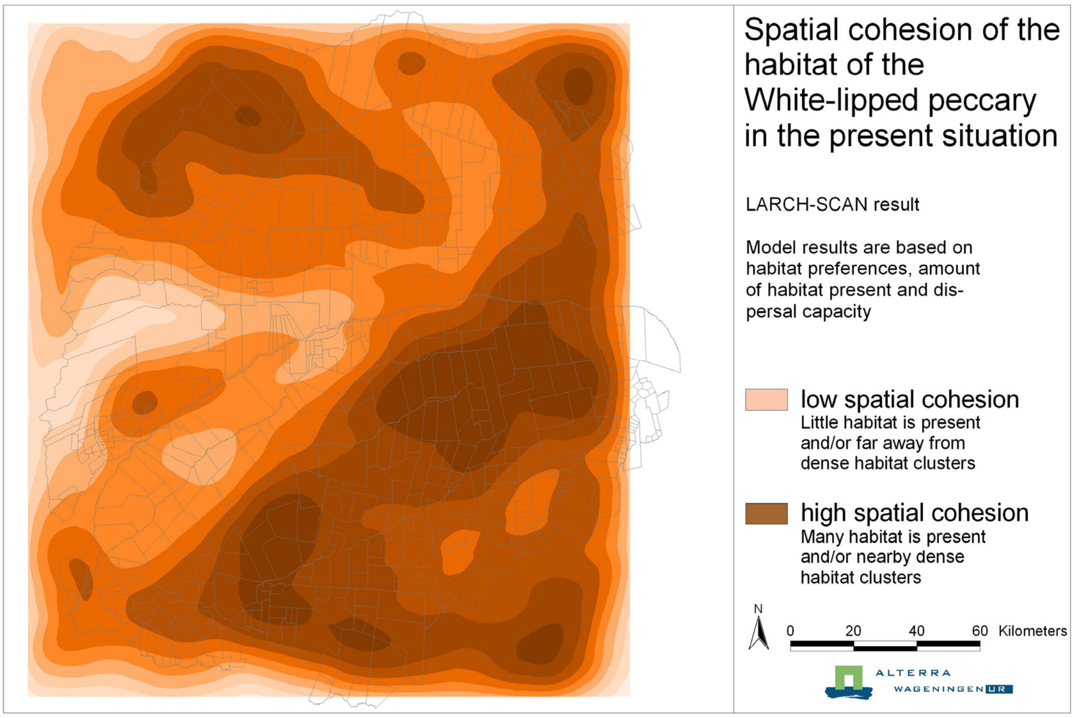


Figure 7.26 Spatial cohesion for the White-lipped Peccary in the present situation generated with LARRCH-SCAN

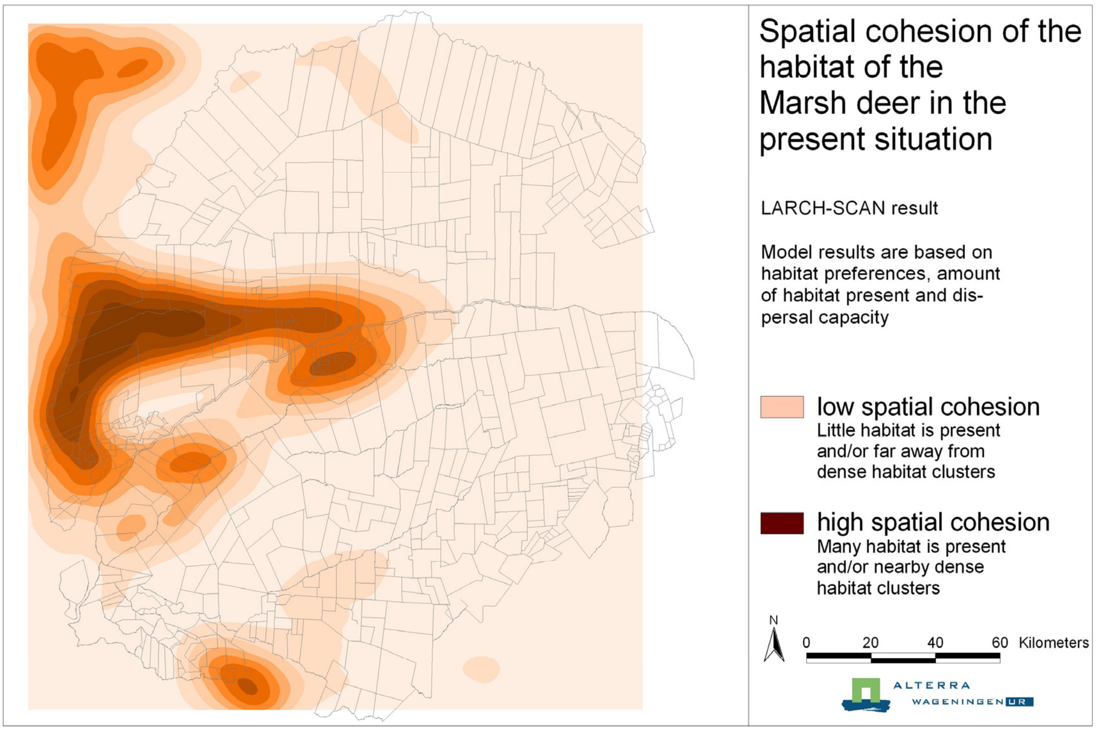


Figure 7.27 Spatial cohesion of the habitat of Marsh deer in the present situation, generated with LARCH-SCAN.

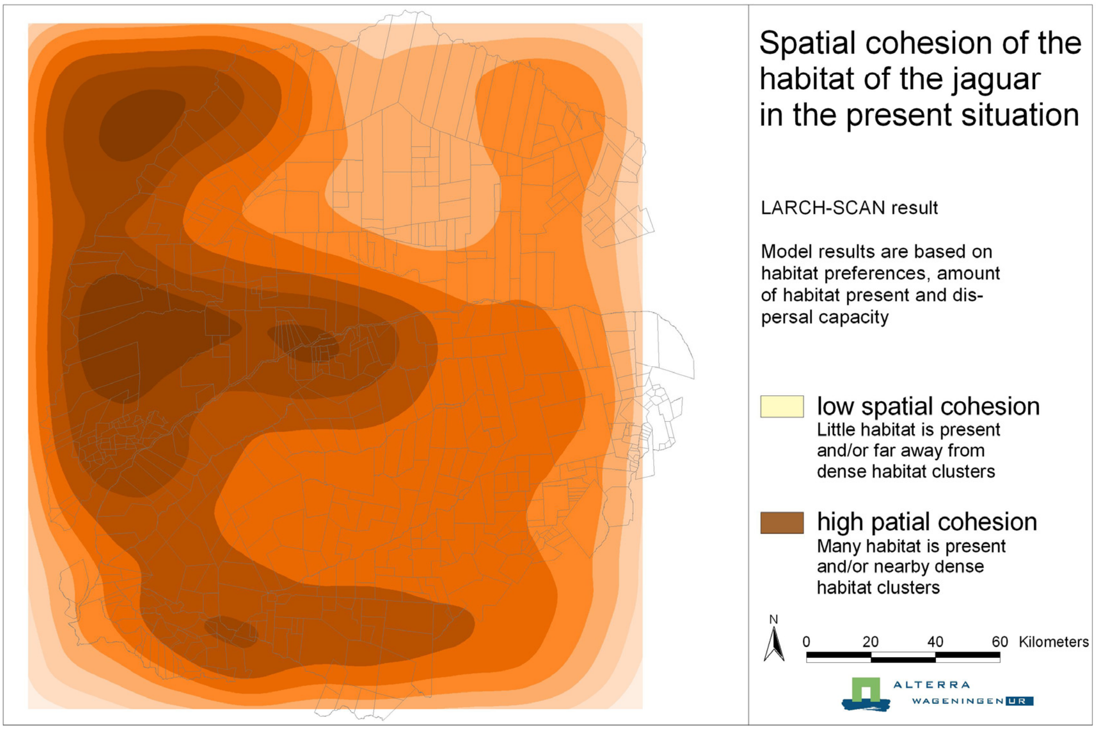


Figure 7.28 Spatial cohesion of the habitat of Jaguar in the present situation, generated with LARCH-SCAN.

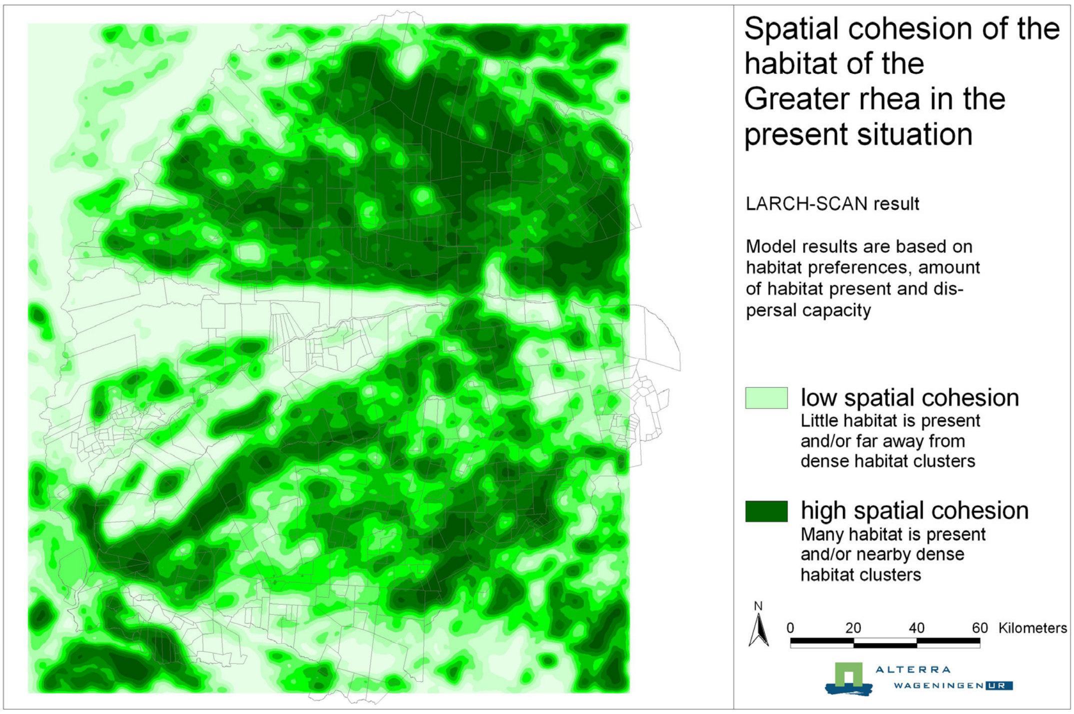


Figure 7.29 Spatial cohesion of the habitat of Greater rhea in the present situation, generated with LARCH-SCAN.

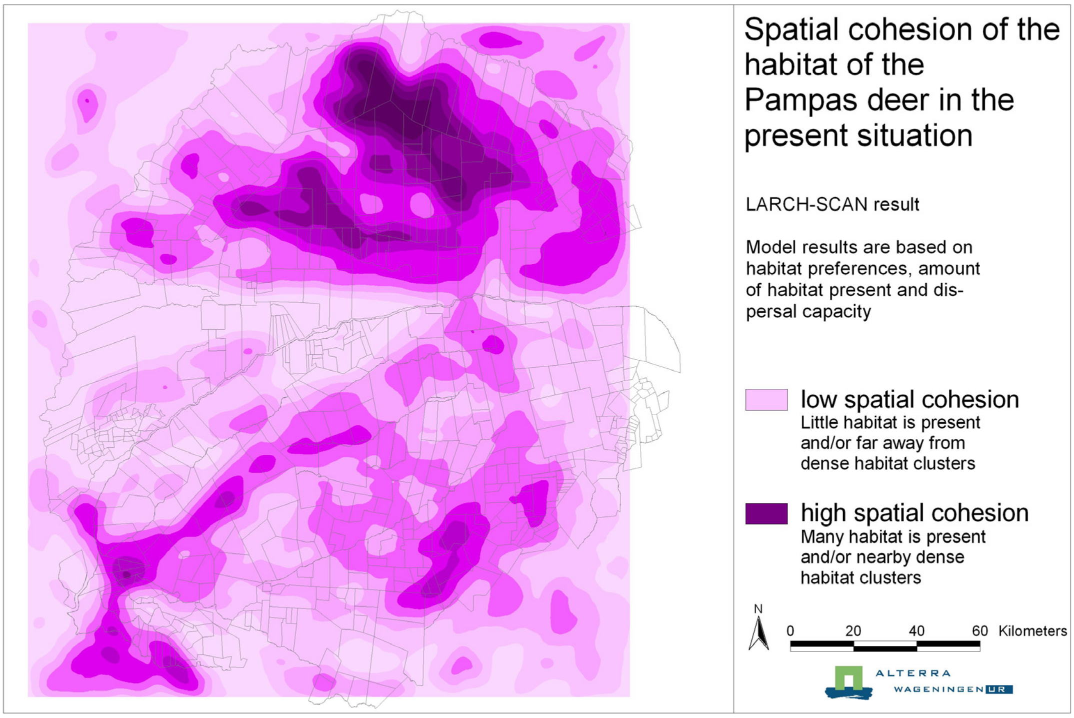


Figure 7.30 Spatial cohesion of the habitat of Pampas deer in the present situation, generated with LARCH-SCAN.

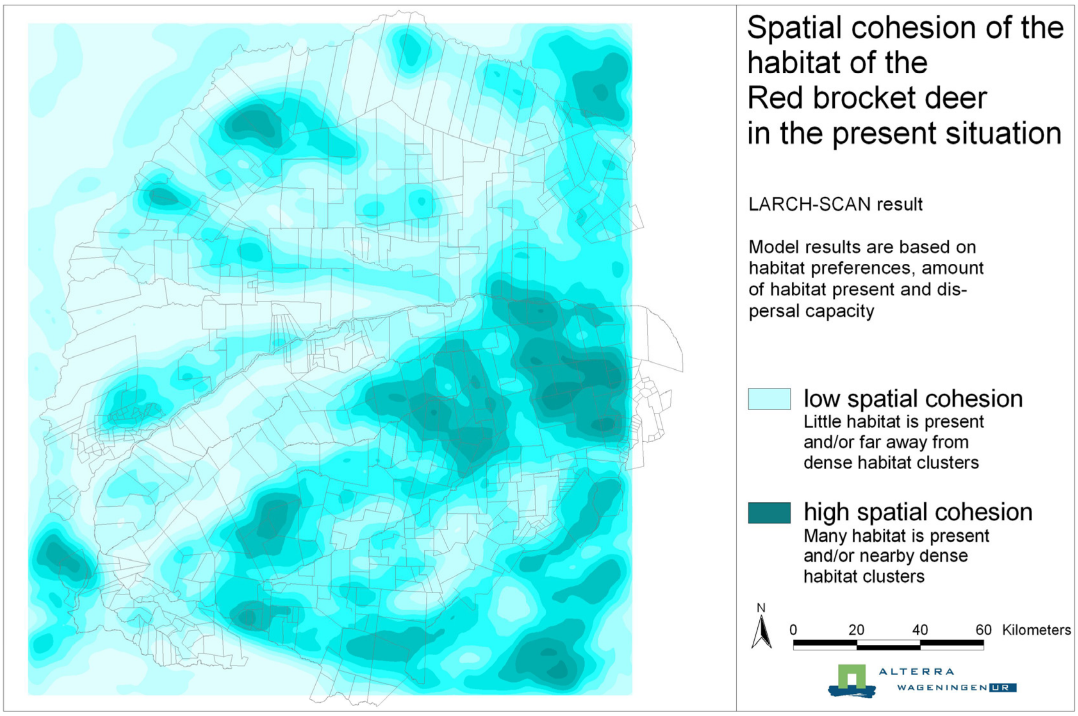


Figure 7.31 Spatial cohesion of the habitat of Red Brocket deer in the present situation, generated with LARCH-SCAN.

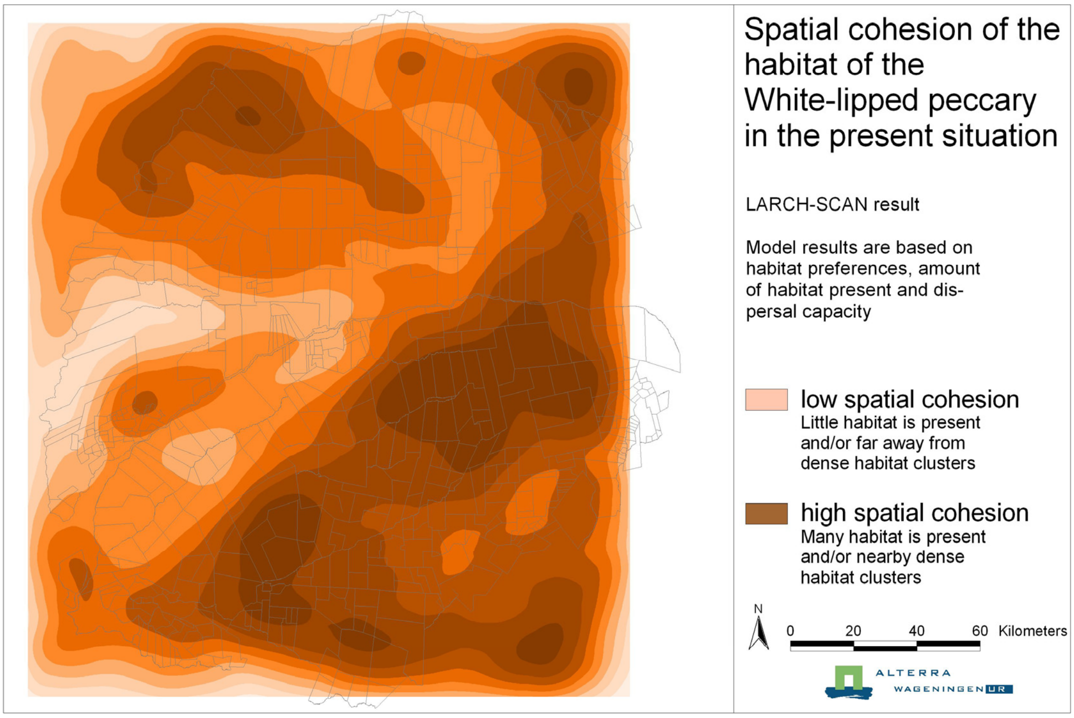


Figure 7.32 Spatial cohesion of the habitat of White-lipped peccary in the present situation, generated with LARCH-SCAN.

7.3.4 Modelling of effects scenarios on species (LARCH-classic)

In Figure 7.33 to Figure 7.37 the effects of the wet and dry scenarios on the habitat of the assessed species are shown in comparison with the present situation. Effects are expressed as changes in carrying capacity of the area; the potential number of reproductive units (e.g. breeding pairs) that the area can sustain is indicated. Also the relative increase or decrease that can be expected in the dry or wet scenario compared to the present situation is given in percentages. This relative figure shows the sensitivity of the species for the dryer or wetter circumstances. At Alterra and EMBRAPA Pantanal reports are available with absolute figures on the carrying capacity of the study area for the assessed species. Also the quality of the populations in the present situation and in the scenarios is indicated.

Species as the Marsh deer, that has its optimal habitat in pioneer vegetation that is under influence of flooding by the river, react very strong to dryer circumstances. In the dry scenario a decrease of 80% can be expected (Figure 7.33). Their specific type of habitat decreases very much in the dry scenario. Instead of this type of vegetation, pioneer vegetation the transition ecotope, ecotope 4) increases. This does not that offer a good quality habitat for Marsh deer (see Figure 7.25).

In case of the wet scenario, the Marsh deer will react also very strongly. In this scenario, a vast larger area becomes under the influence of flooding by the river, resulting in a larger area of pioneer vegetation (ecotope 11 – 13, Figure 7.25), which offers optimal habitat for Marsh deer. In the Wet scenario, the carrying capacity of the total area increases with 80 to 90%!

The same strong effect is to be expected with species for the Giant otter and Yellow anaconda. In case of a dry scenario, the carrying capacity for these species will decreases with respectively some 70% and 60%. In case of a wet scenario, in particular the Yellow anaconda can profit; the potential numbers of this species can increase 43% due to the rise in area of pioneer vegetation under influence of the flooding of the river (ecotope 11 – 13) in the same way as the Marsh deer. For the Giant otter however, the increase in numbers that can be expected in the Wet scenario is not that high (10-20 %); they do not profit of the increase of pioneer vegetation as they area confined to the corixos and permanent waters, that do not increase that much in area.

Species like the Jaguar that also find their habitat in frequently flooded areas however will suffer less in case from the dry scenario. This species has its habitat also in wet areas, e.g. gallery forest, but in case these forests become dryer, it stays suitable as habitat. Also, Pioneiras (Transicao; ecotope 4, see Figure 7.25) that emerges instead of pioneer vegetation under influence of the river (ecotopes 11 – 13, see Figure 7.25) offers suitable habitat for this species. As a result, the carrying capacity of the area stays more or less the same for the Jaguar despite of the transitions of ecotopes; Good quality habitat disappears and develops to the same extent, although it might be located differently.

The effect of the wet and dry scenarios on species that are confined to dryer habitats is less strong than the effect on most species of wetter habitat types. However, it still can be substantial. The carrying capacity of the study area for Red brocket deer e.g. will increase with 30% in the dry scenario and decrease with 20 % in the wet scenario (Figure 7.34). The increase in the dry scenario is mostly due to the increase in the area of dry savannah forest and arboreal that is to be expected (ecotope 5 and 6; see figure 7.25). In the wet scenario the decrease in area of these ecotopes results in a lower carrying capacity for this species.

Also the White lipped peccary shows an increase (20%) and decrease (20%) due to the dryer and respectively wetter conditions in the scenarios, especially in the downstream Taquari floodplain area (Figure 7.35).

For cattle and Pampas deer, the most suitable areas of the frequently flooded savannah gramineo lenhosa will be transferred into the dryer, non flooded variant that has less carrying capacity for these species. Therefore, the high densities of these species north of the Taquari river disappear in the dry scenario. The carrying capacity of the study area for these species levels out because in other areas, the carrying capacity increases. In the wet scenario, the area that has potential for relatively high numbers of these species expands north of the Taquari River, but is also found in some areas in the South (Figure 7.36, Figure 7.37). The overall increase or decrease of potential numbers is not very high (maximum is a 10% increase of cattle in the dry scenario). However, the distribution of suitable area for these species will change: in case of the wet scenario the differences between suitable and unsuitable areas increases, in case of the dry scenario, the suitability for these species remains the same throughout the area. In the wet scenario, the conditions in some areas become much more unfavourable (permanent water). The effect on the carrying capacity is mitigated as a result of the increase in carrying capacity in the frequently (but not always) flooded areas.

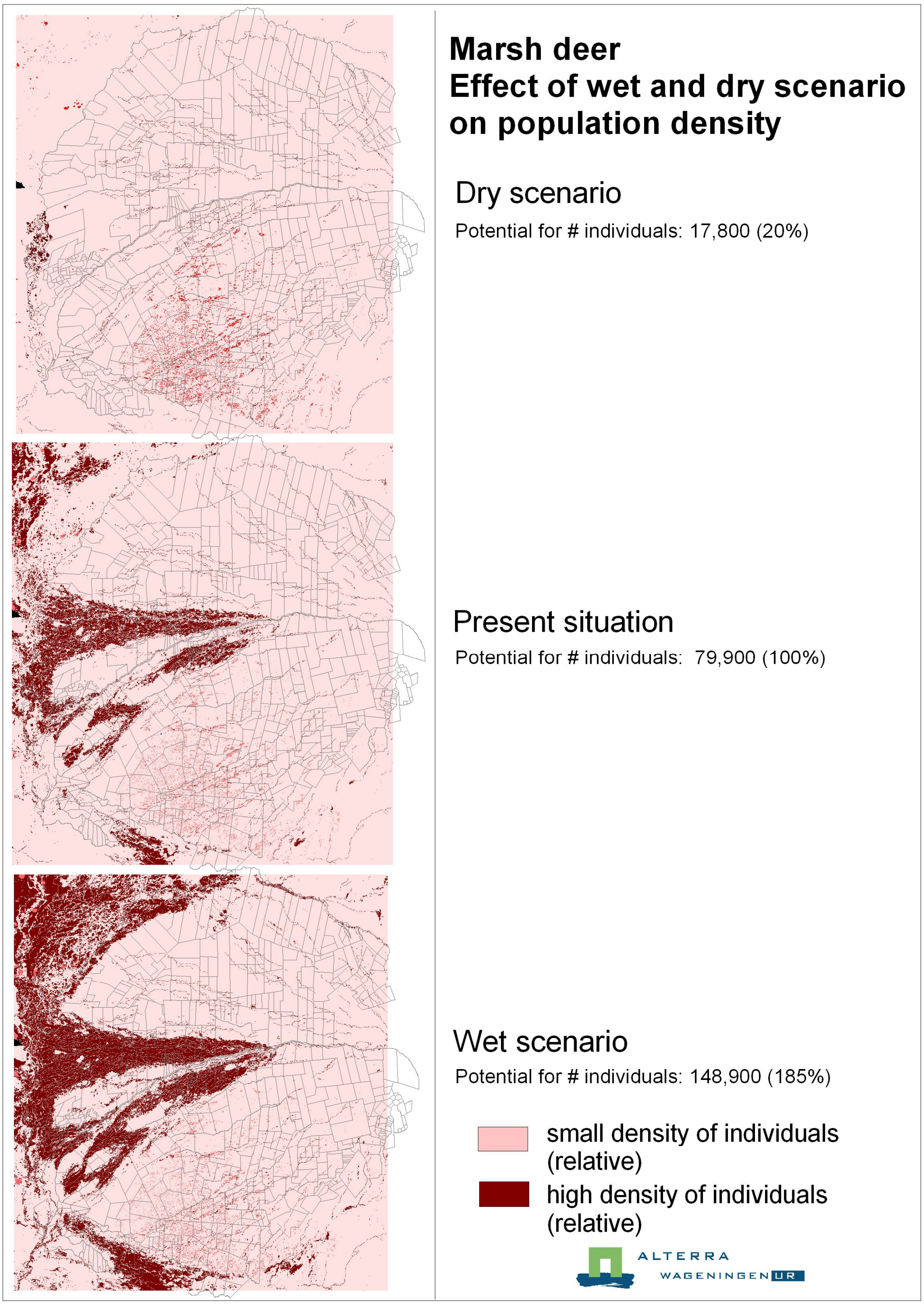


Figure 7.33 Effect of the Dry and Wet scenario on the habitat in and carrying of the study area for Marsh deer.

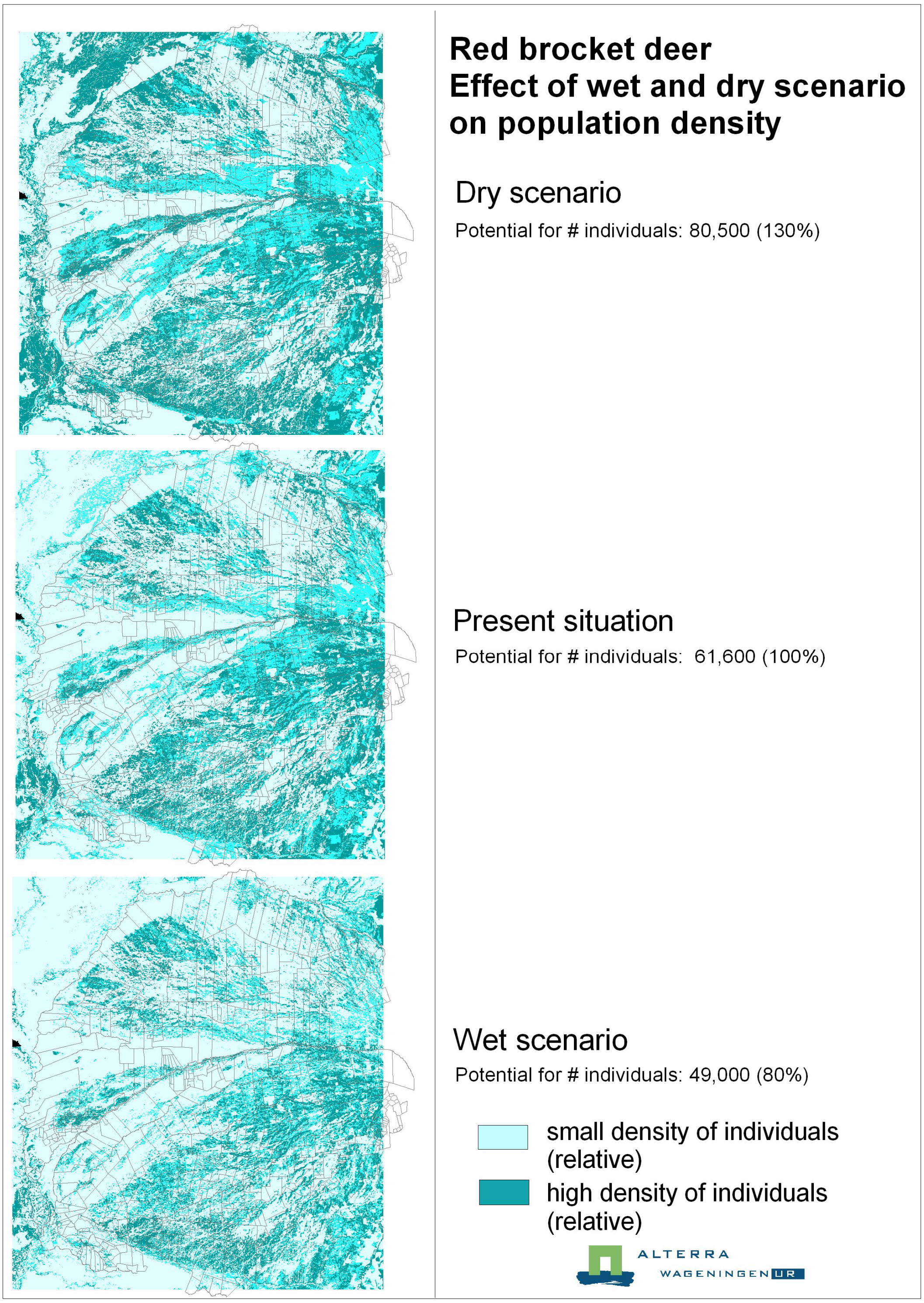


Figure 7.34 Effect of the Dry and Wet scenario on the habitat in and carrying of the study area for Red brocket deer.

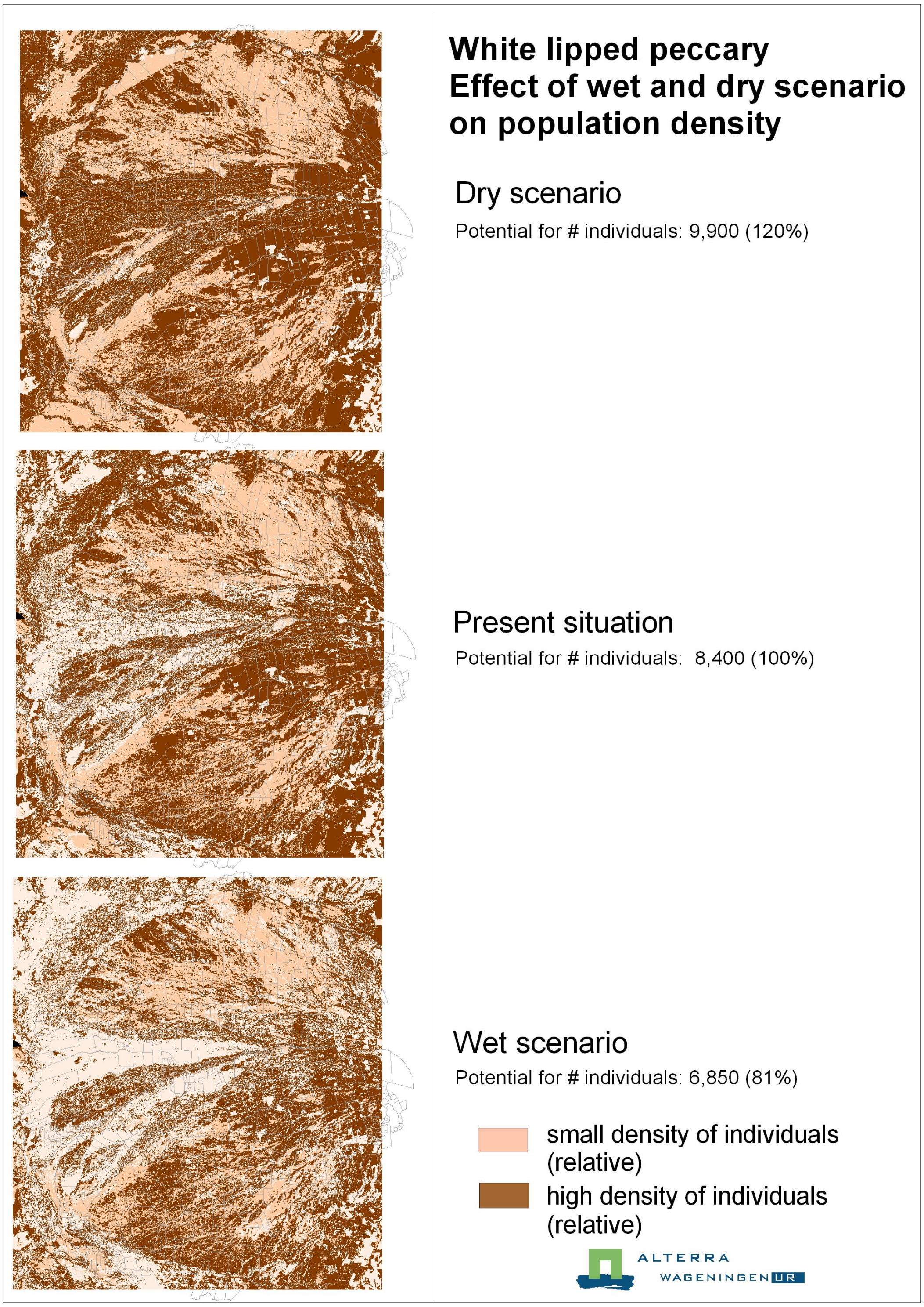


Figure 7.35 Effect of the Dry and Wet scenario on the habitat in and carrying of the study area for White lipped peccary.

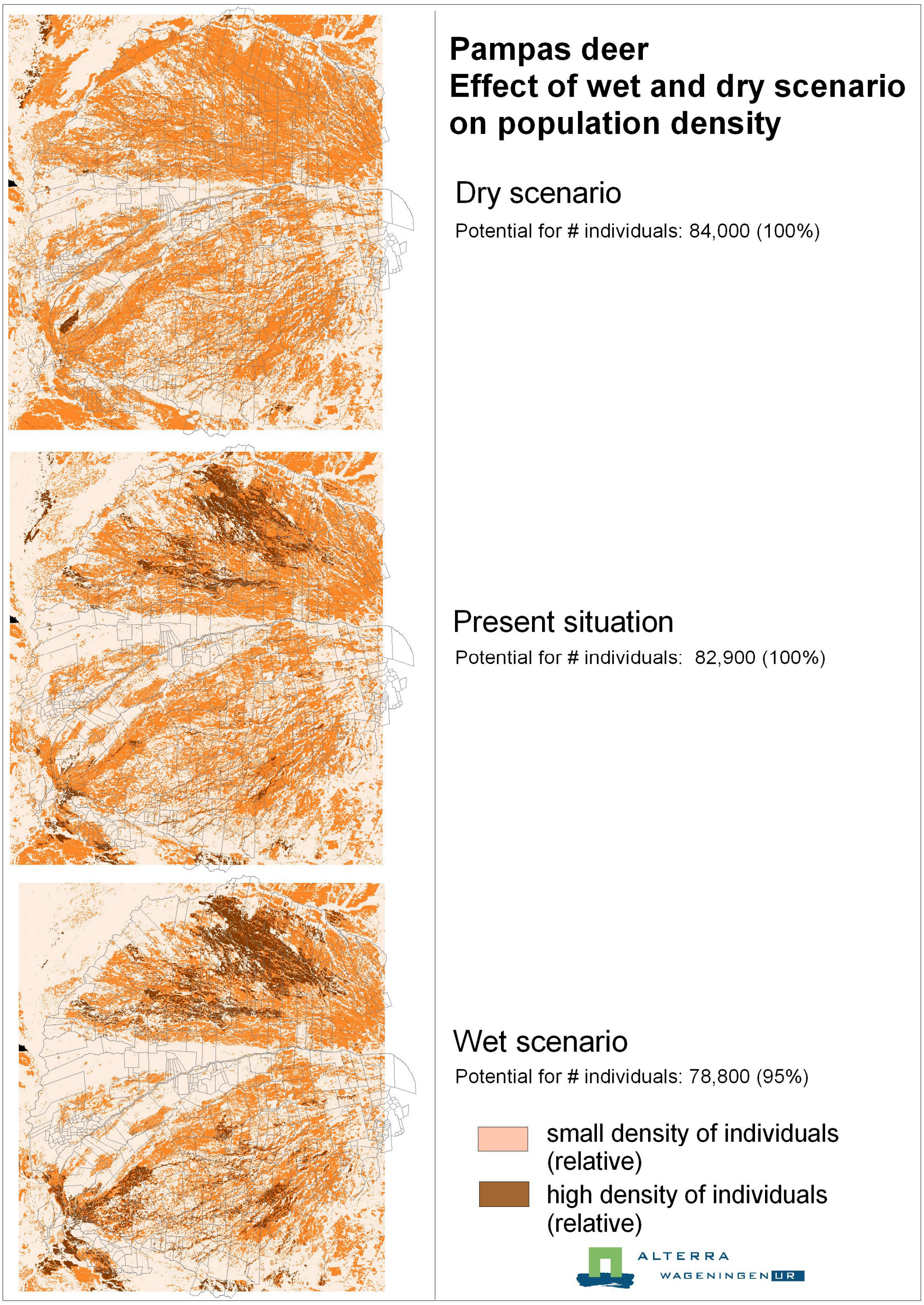


Figure 7.36 Effect of the Dry and Wet scenario on the habitat in and carrying of the study area for Pampas deer.

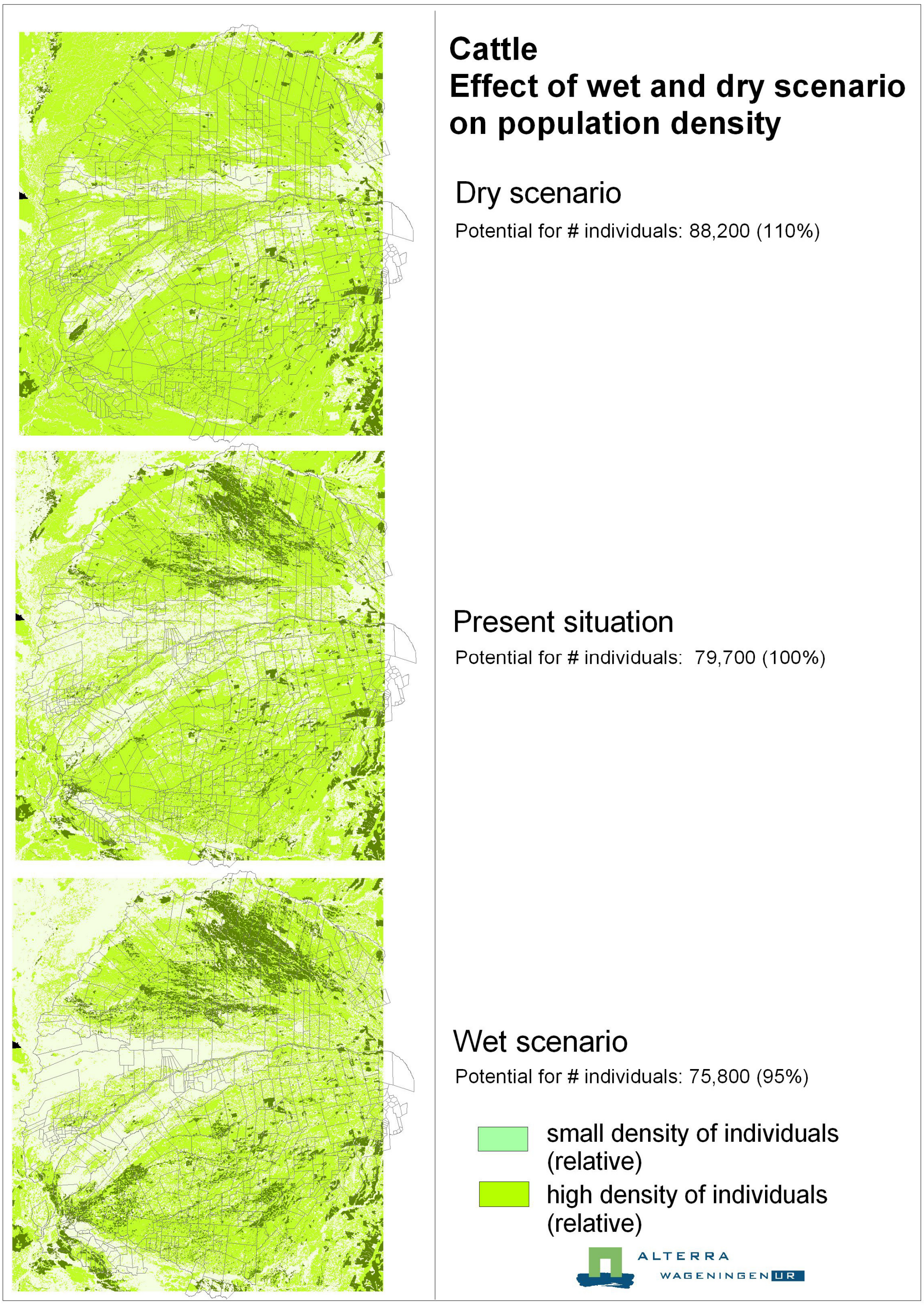


Figure 7.37 Effect of the Dry and Wet scenario on the habitat in and carrying of the study area for Cattle.

7.3.5 Discussion and conclusions

The method that is used combined the regional knowledge of field and species experts and methods landscape ecological modelling. The results on the ecotope maps and distribution and abundance of (non or semi aquatic) species are checked by several field experts and appear to provide a truthful image of the Taquari area. This detail of spatial information of the area was not available yet. The results herewith provide a good basis for further exploration of the situation in the Taquari area and the landscape processes in this area as well as its potential expansion to the whole Pantanal.

The models for modelling ecotopes and ecological coherence have been calibrated and validated for the Taquari area. A small number of scenarios has been assessed to analyse the effects of changes in land use on species. With this experience and model settings, it is possible to develop and assess future scenarios for this area. Also the model setting can be used as a starting point for assessment of other parts of or the entire Pantanal.

For aquatic species, a set of ecoprofiles have been constructed. However, for these species, less information is available on habitat characteristics, abundance and life history. To make a spatial analysis of the habitat suitability for aquatic species, more and different data are needed than available at present. That should make it possible to develop more detailed ecotope maps of the aquatic environment, tailored to the habitat requirements of aquatic species of interest. A pilot study on aquatic habitat, processes and species on a case study level, is then recommended.

Conclusions on the assessment of the viability of species:

- The effect of some extreme scenarios has been assessed. With the result of these assessments, the effect of all kind of measures on the presence and the cohesion of habitat and its effect on the viability of species have been estimated. Effect of measures for the mitigation of on undesirable flooding on the distribution of individual species has not been assessed.
- Based on the results of the scenario analysis the effects that can be expected of plausible measures will be assessed further in chapter eight.
- The overall effect of the extreme wet and dry scenarios on the carrying capacity of the Taquari area is not very large for most species; some parts of the study area become not suitable, whereas other parts of the area become more suitable. Only for species linked explicitly with wet or dry habitats the affect is larger.

8 Socio-economic aspects stakeholders and decision making

Rob Jongman[23], Helena Berends[24] and Luc Boerboom[25]

For decision making participation of stakeholders is important. They have been involved in the project in all phases. In the first meeting the problem of the Taquari has been discussed with all stakeholders, local and regional authorities, farmers, NGOs and researchers (Figure 8.1). This has led to the problem statement as formulated in chapter 1. In later phases the contact with stakeholders and authorities involved has been maintained through direct contact (Agência Nacional de Águas, Secretaria de Recursos Hídricos) and stakeholder meetings. Also a workshop has been organized with individual knowledge bearers from the region for participation in the scenario building. Several workshops have been held during the project. One was held with local knowledge holders on the species in the Pantanal to create the scenarios.

Figure 8.1 Active participation in the first Stakeholder Workshop, Corumbá 2003.

In the first workshop the knowledge from Brazil and the Netherlands has been compared and matched; the problems and the possible solutions discussed. Already in this workshop

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the disappearance of the flood pulse in the Taquari basin as important mechanism was one of the foci in the discussion. The decline of fish stock id data are compared for the periods: 1979 until 1983 and 1994-1999 ids obvious. . In the first period fish was abundant, but this is now reduced especially in the river Taquari. The cause of this reduction can be found in the disruption of the flood pulse. The regular flooding of the Pantanal area provides the river water with an influx of organic material which is food for many fish species at the bottom of the food chain. Statistics show that especially the fish on the basis of the food chain have become greatly reduced in the river Taquari with enormous consequences for the whole ecosystem.

In this first stakeholder meeting the farmers were well represented and they are the other party that suffered from the flooding of the Taquari. Some have reduced production capacity and some have even lost their land.

How the possible outcome should be evaluated has been introduced and discussed as well. It has been concluded, that when evaluating plans and policies it must be considered that:
- Measures to protect the environment are not always non-economic. On the contrary, there are many examples where nature and economy have both benefited: like recycling and saving energy.
- It should be possible to value the importance of nature. Up to now, there are different ways to assess the value this, such as the objective of visiting and the relation with the ecosystem involved. That gives a link with local or regional economy.
- It is important that people participate, because participation appears essential when dealing with public-private interactions.

How people can participate and where their influence is situated has been demonstrated by the example from Mato Grosso on the Upper Paraguay River. The perception of these stakeholders on the ecological, social and cultural aspects of the spatial changes in the area was presented including an overview of the levels of influence, interaction, and relation of competition and collaboration among stakeholders. The stakeholders can be roughly divided into four groups:

1. Public representation such as the Ministry of Environment, Agência de Águas, IBAMA
2. Land owners, Enterprises
3. Local NGOs, local forum, community associations
4. Public policy: Transportation, Waterway (Hidrovia), Energy (dams), Fishery legislation, Tourism, Pantanal Program

It was conclude that committees and councils can facilitate an integrated and participative management of the Pantanal as long as it includes all stakeholders and is based on local social organization; as long as it strives for consensus and decentralizes power and guarantees a process of decision making that is equitable and transparent.

From this first workshop the following conclusions have been drawn:
- The local fish population has been impoverished by the breaking of the food chain. According to the people involved the reaction of authorities to the problems has been late; care must now be taken that all stakeholders will be treated equally in the process, but with special attention to the local population who has suffered most. The law must

be used to protect environment and people likewise. At the moment the law is not always in line with the wishes of the local people. The project is designed to help stakeholders to make a decision on the solution of the problem. The Taquari area is highly sensitive and therefore one should not rush to a decision.
- The hydro-electrical companies have established already 60 water committees which are democratic and participative. The Taquari region urgently needs water boards like these. The government has started the process by establishing Technical committees, who are developing an Action Plan and starting pilot projects with aspects in participation and monitoring.
- Attention should be given to the livestock sector as an important economic factor in the region.
- LEDESS is not used for simply assessing cause and effect, but is structuring spatial knowledge and shows effects of measures taken.

The farmers' organization proposed a number of possible solutions, such as:
- constructing a dam to keep the sediment from coming into the river
- to re-establish the flood pulse and therefore remove sand from the river bed.

The Pantanal-Taquari project will assist the stakeholders in their search for a solution, but it must first create an understanding of this complex problem. Important is that all parties are involved and that solutions will benefit all and not reallocate problems.

During the project contact has been maintained with the stakeholders in several moments. Communication has taken place between the research groups and stakeholders at various levels (authorities (ANA, Ministry of Environment, FEMA, IMA-P), agricultural and environmental non-governmental organizations, researchers, individual farmers and fisherman and people in the street.

With people in the Corumbá interviews have been held to develop insight in their visions and ideas. The questions asked were:
- What do you see happening in the Pantanal?
- What does the Pantanal mean to you?
- What is your dream for the Pantanal?
- What needs to be done to reach this dream?

This resulted in three social scenarios:
- Using and developing the natural resources carefully: This future is based on cattle breeding and fishing, allowing for (non predatory) tourism, with sufficient social services for the local population. It is a continuation of the existing development path, but with more attention to nature conservation and to social services
- Conservation scenario: Many people mentioned the beauty of the Pantanal that needs to be preserved. In this scenario the region is a nature sanctuary, to be visited and enjoyed by those who love it and for research purposes. It requires international and national funding. (The example of the Mamirauá reserve in the Amazon shows that this is possible.)

– Bringing industrialisation to the region: Many people mentioned the gasoduct with Bolivia and the plans to make an electricity generating plant and new industries in Corumbá. This would provide jobs, reduce poverty and make the conservation of the Pantanal possible, many thought…

Figure 8.2 Interviews in the streets of Corumbá

A special workshop has been held for training of EMBRAPA and university staff on spatial decision support methodology. Staff from both EMBRAPA and the university was enthusiastic about concepts of spatial decision support systems discussed. Sessions were even extended to gain more depth.

By differentiating between scenarios (i.e. changes of the uncontrollable system environment) and alternatives (i.e. changes the controllable/manageable system) it could be shown that the existing list of alternatives (Table 8.1) was really a mix of scenarios, alternatives and even criteria, each addressing different problems and therefore most not being alternative solutions to the same problem.

The absence of a decision unit where stakeholders define common problems, to which alternative solutions are sought at an appropriate scale of control, is an important reason for the confusion. Moreover, the absence of an evaluation structure for alternative solutions before they are being developed prevents the design of solutions (i.e. value-based design) which actually address the problems.

Table 8.1 List of alternative solutions for the Taquari problem

Nr	Solution
1	Business as usual
2	Closing side channel
3	Stop erosion in the highlands
4	Impact barriers: paved roads
5	Hidrovia Paraguay
6	More floods and precipitation (scenario)
7	Less cattle more fire (impact)
8	Dredging Taquari
9	Dam at Coxim
10	Organized maintenance (river management)
11	Financial compensation for farmers
12	National park
13	Help Coronal river form its bed
14	Improve cattle production
15	Corumbá/Pantanal development alternatives
16	Industrial development
17	Conservation development
18	Tourist development

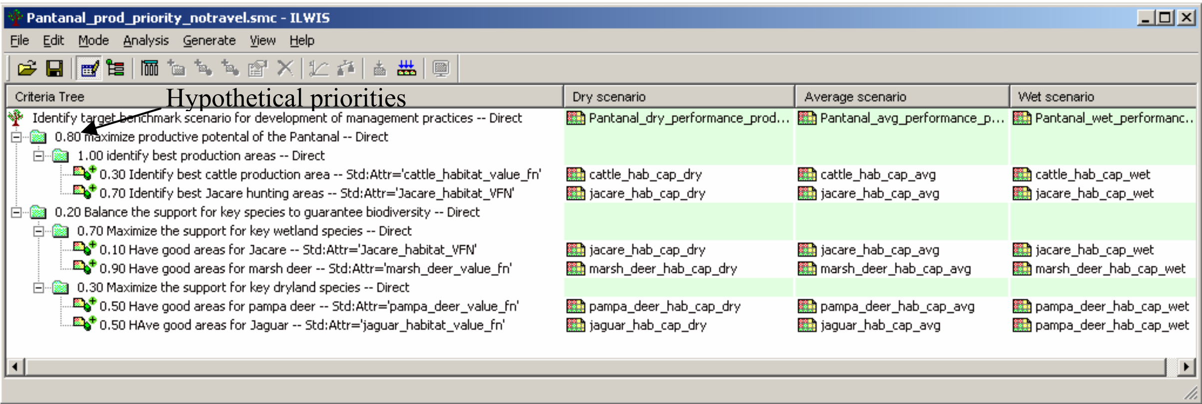

Figure 8.3. Hypothetical decision problem structure, to evaluate performance of the Pantanal under three different hydrologic conditions.

Principles of decision making and the need for a decision unit were discussed as well as the principles of multicriteria evaluation. Also, an example spatial multicriteria evaluation was performed in ILWIS (Figure 8.3) using the habitat capacity data generated by the Pantanal Ledess model. Three scenarios as depicted in chapter 6 (dry, average, and wet scenario) were evaluated to demonstrate the principles of spatial multicriteria evaluation. The underlying decision concept was that in the absence at this point of alternative solutions, an evaluation of scenarios could obtain insight whether eventual alternative solutions should aim to make certain areas in the Pantanal drier or wetter. In the absence of a formalized evaluation structure and priorities, hypothetical structure and priorities were used (Figure 8.3).

Also, hypothetical value functions (Table 8.2), which give utility to the data and standardize the different dimensions/units of the criteria to the same dimensionless scale, were used. Although hypothetical, these value functions might very well approach real value functions, but they have not been reviewed as such and at this point there was not much sense in doing so.

Table 8.2. Hypothetical value functions.

Table "habitat_capacity_value_functions" - ILWIS

	cattle_habitat	jaguar_habitat	Jacare_habitat	marsh_deer	pampa_deer_value_fn
No habitat	0.00	0.00	0.00	0.12	0.00
Marginal habitat	0.10	0.10	0.10	0.28	0.30
Medium quality habitat	0.50	0.50	0.50	0.52	0.50
Optimal habitat	1.00	1.00	1.00	1.00	1.00

The example leads to a spatial evaluation of overall performance of the Pantanal alluvial fan area under different hydrological conditions (Figure 8.4). Due to the structuring of the problem the wet conditions are preferred, because this hypothetical analysis assumes Jacaré hunting areas to be of main interest

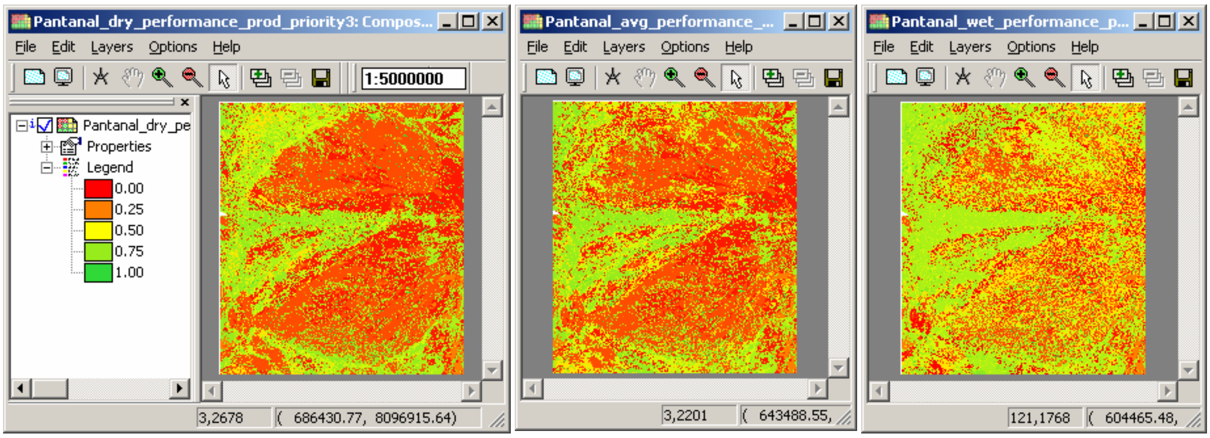

Figure 8.4. Overall performance of the Pantanal alluvial fan area under different hydrological scenarios (dry, average, and wet). Green areas perform well and red areas perform poorly, given the criteria structure, the prioritization of criteria and assessment of value functions.

On November 23 2004 the final results were presented at the Sindicato Rural, the farmers' organisation. Causes, scenarios and technical solutions have been discussed. Present were about 70 persons, farmers, members of NGO's, EMBRAPA staff, officials from policy.

After the presentations of the research results and the analysis of the potential solutions (see chapter 8) a lively discussion started on the results and the possible solutions. The conclusion was that there are several technical and economic options, but the financial situation makes it best to look for the cheaper solutions. All agreed that solutions downstream have to be integrated with upstream solutions. The meeting decided at the end to set up a working group of all stakeholders to bring solutions into practice and be a partner for other groups in the river basin. This means the objective to support the region to take decisions on water management has been reached. The participants were satisfied with the results of the projects and many complemented the team with the results of only two years work.

9 Solutions, possibilities and costs

Rob Jongman[26]

9.1 Introduction

The solutions to the problem of flooding that have been suggested by the stakeholders and authorities are the following:

- Dredging of the Taquari
- Closing of the Caronal Avulsion
- Prevent new avulsions
- Help the rive to create new river channel from the Caronal to the west
- Construction of dikes
- Construction of a dam
- Prevention of erosion by planting Forest along rivers on the Planalto
- Prevention of erosion by capacity building on erosion and river management
- 'Doing nothing' but buy out the inundated land

All possible solutions have seriously been analysed by the team in some working sessions with external support especially to bring back the solutions to cost levels that reflect the situation in Brazil.
The solutions have been analysed using the results of the project as a reference. The aspects that have been considered are

- Technical feasibility
- Ecological and land use consequences
- Costs

In the analysis and the valuation of the results the scope has been that the Pantanal should remain a world Natural Heritage site and its functioning as a wetland should not be endangered. That was also an important reason to look for solutions. The regional and local situation should be improved in a sustainable way, developing long term solutions. The costs must be reasonable for the region and the people involved.

9.2 Analysis of the solutions

9.2.1 Dredging of the Taquari

The distance of the river stretch to be drained is about 350km. If a depth of 3 metre is accepted making the river accessible for ships, the amount of material to be dredged has

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been calculated as 60.000.000m^3, not including the daily increment. This increment can be based on the 2000m^3 daily sediment discharge at Coxim in 1995 (Padovani et al 1998a). Part of the daily sediment discharge will be in channel and part will be overbank sedimentation. How the division between the two categories is, is unknown. The ships that are available in Corumbá to do this job can dredge 300m^3 per hour. If three are available the time needed to do this is 10-30 years and the costs are estimated on R$ 180.000.000 based on figures for dredging the Paraguay not including the daily increment.

If drainage is started then it must be set up as a continuous activity; drainage cannot be stopped without losing it effect in a relatively short time. There is need for a supervising organisation, but finally the river pulse, biodiversity of terrestrial species and populations of fish will recover. Part of the land gets relatively dryer (Figure 9.1).

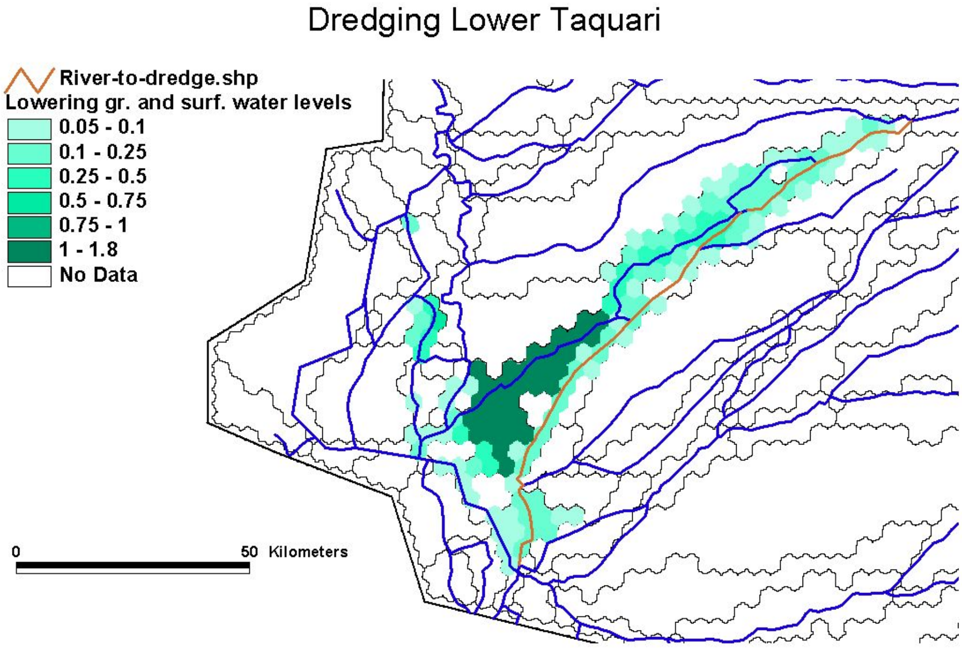

Figure 9.1 Potential effect of lowering the flooding the Taquari river bed

9.2.2 Closing the Caronal avulsion

Closing the avulsion at Caronal can only be carried out after or in combination with the river dredging. If this is not done in combination then other areas around the existing Taquari will be flooded (Figure 9.1). For the drainage hard material must be used, because the area involved is unstable. Based on the transport route, the distance and the costs elsewhere the estimated costs are R$ 3.500.000

Consequences are that there will be less water in Paiaguás, but there is no guarantee that the original situation will return, because as can be concluded in chapter 2 and 3 the situation is very sensitive. The logical direction for the Taquari to move its bed is the direction from Caronal to the west. There will always be a tendency that the river will form a new bed in this direction.

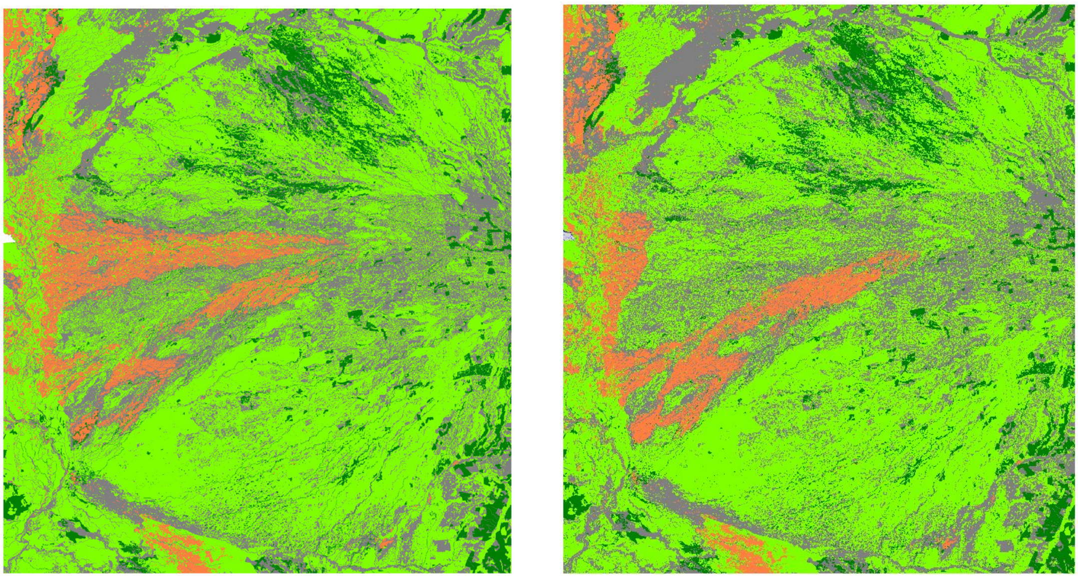

Figure 9.2 Changes after closing the avulsion of the Caronal (left before closing, right after closing)

Closing of the avulsion without dredging the river will have no consequences for cattle breeding and biodiversity in general as the wet/dry area ratio will remain more or less the same. The closing will only reallocate wet and dry areas. The farmers along the Taquari will have to meet more floods and in Paiaguas less. Species related to wet conditions will also swap position.

9.2.3 Prevent new avulsions

The instable zone is downstream of Figueiral (east of Caronal, see Figure 4.1) is about 300km long. Prevention of avulsions is a continuous activity and should be supervised by a management organization. New avulsions can be natural or illegal and man-made (see chapter 1 and chapter 2). It is not well possible to estimate costs for this activity. It might be expected that the situation will be stable in the first years, but the possibility of new avulsions will increase after some years, because sedimentation in the river bed continues The impact on cattle breeding and biodiversity will be neutral as there is no change in wet and dry areas.

9.2.4 Create a new river bed from Caronal westward

It is also suggested that a new channel, that is developing at this moment west of Caronal could be dredged out artificially to create a river bed. The distance to the Paraguay is about 230km. If a depth of 3 m is taken then bout 80.000.000m^3 should be excavated. The time needed for this is depending on the equipment available but can be estimated between 10-30 years and the costs can be estimated at about R$ 240.000.000.

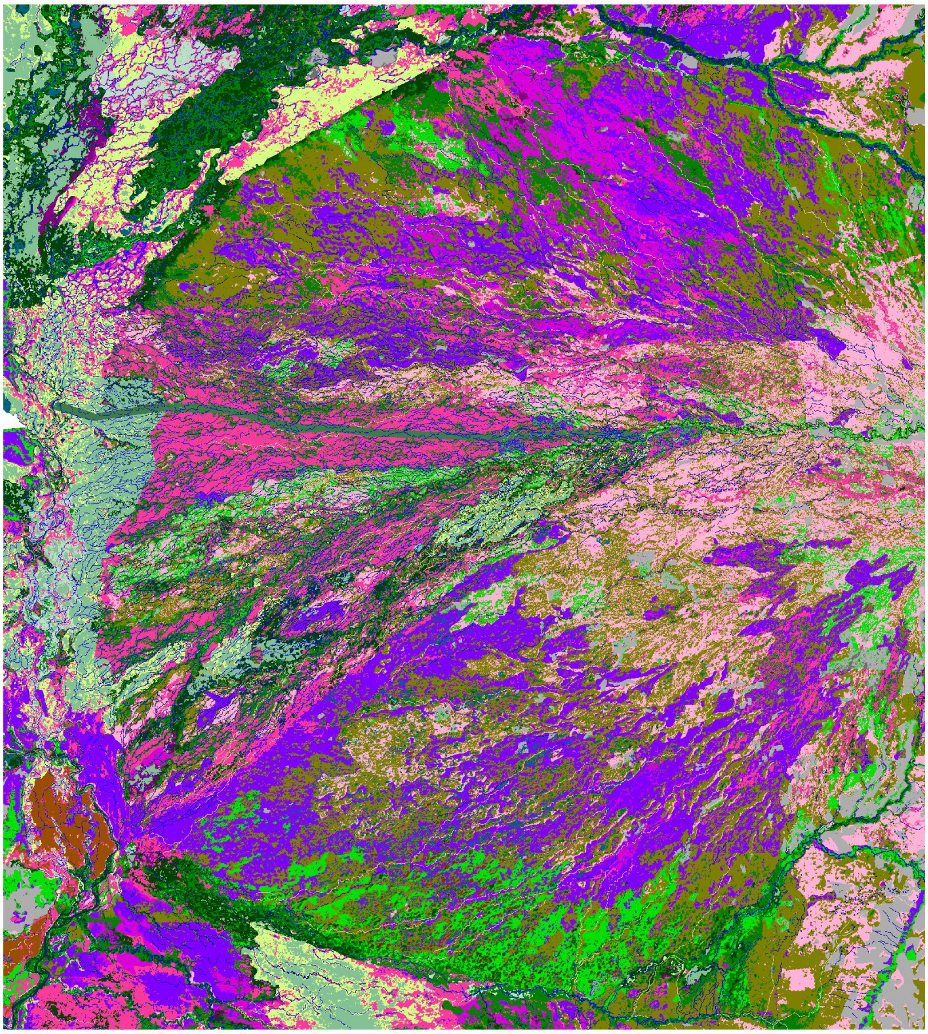

Figure 9.3 Consequences of a new bed for the Taquari after realisation

The consequences are that there are on the long run less inundations in this part of Paiaguas but the old riverbed will dry out as all the water will go the new direction (Figure 9.3) This might cause transport problems for the farmers in that region. They might have to use the roads over Nhecolândia or keep some waterways open.

For cattle breeding and biodiversity this solution means that at least after the channel is created that there will be a period of better drainage and discharge. There will then be more land available for cattle breeding and species using dry land will be favoured. If the flood pulse returns it also means that the fish population will recover.

However, although the solution seems promising, it is rather expensive and how the sedimentation process will continue and what this means for the new channel is also not yet included.

9.2.5 Construction of dikes

The subsoil of the downstream stretch of the river consists of erosive and instable material. The material needed for stable dikes is not available and should be brought in from elsewhere. Moreover dikes need permanent supervision. The costs are difficult to establish as these depend very much on the type of dike that is wanted, transport costs and the way they have to be built. These uncertainties and the expected high costs make that this solution is not considered to be realistic.

9.2.6 Construction of a dam in the Planalto

Dam construction for retention of sediment can be done on one place or on several places in the Planalto. The more places are selected the lower the dam can be and the lower the costs for each dam. If the dam is used for other functions as well, such as water storage or electricity production, then the dam should be high and will be more expensive. The costs are estimated on the costs of a dam in a comparable river in Argentina that just has been realised (Rio Mendoza). This dam has been made for drainage and electricity production. Estimated costs are

- For a dam for water retention (40m high) and sediment retention R$ 1.400.000.000 (Figure 9.4)
- For a dam for sediment retention (10m high) R$ 20.000.000 (Figure 9.4)
- For three smaller dams for sediment retention: R$ 30.000.000

The consequences are that in all cases the sediment is retained, but it will stimulate downstream erosion as every river needs bedload. If there is only one dam, then the flood pulse and fish migration will disappear or be severely hampered. This means that the fish production will not return in the river and this might cause ecological and economic damage If only three smaller dams are placed for sediment retention, then the impact on the flood pulses and fish migration will be less. However as the Planalto has not been part of the spatial and ecological analysis the real affects cannot be stated without further inspection at the site However as all tributaries of the Taquari originate from the Planalto east of Coxim, the building of a dam can have a major impact on the fish reproduction.

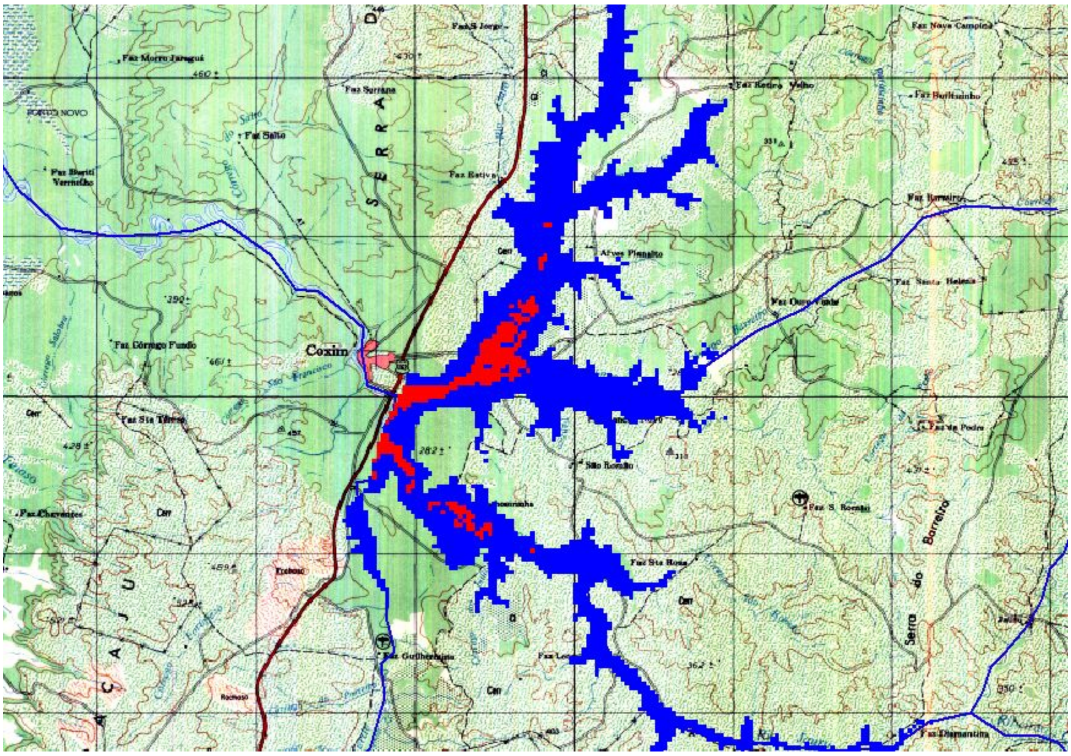

Figure 9.4. Dam for water and sediment retention. Red: only sediment (10 m), blue: water and sediment (40m)

An important consideration in building a dam fore sediment retention is that the sediment will have to be removed regularly and not be passed on to the Pantanal to prevent further sedimentation. Moreover, if sediment enters the Pantanal from the Planalto, it will first be deposited in the east part of the Pantanal and only slowly be transported westward to the downstream area.

9.2.7 Afforestation of river margins on the Planalto

The discharge of the Taquari from the Planalto has increased since the 1970s. There is more water and more sediment transported. A possibility to diminish the increase in water and sediment is replanting forest on the Planalto. By planting forest evapotranspiration is stimulated. The Brazilian Codígo Florestal obliges to keep 10% of the land forested. For the Planalto this would mean an area of 2.700km^2. If this is done in a planned way along rivers and streams, in the most vulnerable areas for erosion, then it might be a tool in river basin management. However, this requires planning and supervision. It also requires that the farmers on the Planalto use pumps for their water needs and prevent cattle to go down to the water.

The costs estimated for this solution are R$ 8.000.000, but it also requires an organisation that is capable of planning and supervision on the actions in the field. Actually such plans should be part of a river basin management plan.

The consequence is decease in erosion and water discharge due to increased evapotranspiration. The consequences for cattle breeding and biodiversity can only be estimated as a long term effect as the river has to stabilise its river bed. How quickly that happens depends on measures taken downstream. If no measures are taken, then this might last several decades, depending on natural developments.

9.2.8 Capacity building and river management organisation

River management organization is a long term solution. Capacity building is part of a long term solution. Training means that teachers will have to be trained to train the organizations and the farmers in sustainable water and land management. Estimated costs are R$100.000 to R$10.000.000 for the whole basin.

The consequences are that joint decisions will be taken, costs can be shared. It is only wise to do this in the context of a river management organisation with supervision and clear tasks in management. There are no direct consequences for biodiversity. It might be advantageous for farmers on the Planalto.

9.2.9 Develop a National Park

One of the solutions mentioned is to develop a national Park in the inundated area. What the costs of such a solution is, depends on the national strategy of developing National Parks. In some countries National Parks are State owned; in other countries they can also be private. In any case the inundated area of maximum of 5000 to 8.000km^2 will have to be compensated when no cattle ranging is allowed. Eventually farmers should be reallocated elsewhere. It is a quick solution for the farmers and a long term solution for biodiversity. If full compensation is needed then the costs will rise to about R$ 100.000.000 to R$440.000.000

9.3 Recommendations

From these solutions it can be concluded that the following actions have the best perspectives:

- Develop an organisation for river management at the basin level;
- Adapt land use to the behaviour of the river as a natural phenomenon;
- Management of avulsions must be done in the context of the ongoing river processes (erosion sedimentation), the environmental conditions (backwater effect of the Taquari, water discharge variability);
- Erosion prevention on the Planalto by application of the código florestal for the river edges is an important measure;
- Compensation of the farmers for the flooding by creating a National Park can be a fast solution;
- Eventual construct some small dams for sediment trapping when needed;
- The technical solutions are too expensive and without perspective when there is no coherent management.

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