Pantanal-Taquari:
Tools for a decision support system

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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 project is now in its last stage and not all results are available yet. The technical basic reports are finished, but its use in scenario building and in the discussion and organization development with the stakeholders is just in the reporting phase and not yet fully included. Still, this document gives a good overview of the actions that were part of this project.

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.

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

Dr R.H.G Jongman
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Content

Pantanal-Taquari: Tools for a decision support system

1 The context of the problem

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1.1 Objectives of the Project

The objective of this Partners for Water project is: “Support the wise use of the plains of the Pantanal Taquarí river catchment, 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 Taquarí river. It has assessed the consequences for the river system, the downstream ecosystems and land use and supports the development of an organisational model for management of the river catchment, in co-operation with and supported by farmers nature conservation representatives, national and state authorities. This is worked out in five strategic objectives.

1. Development and use of a “goal oriented” dynamic approach of modelling of catchment-land use and the river, 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;
2. Inventory of gaps in knowledge and definition of the research and development agenda;
3. 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;
4. Development and use of a transparent process, developing and using tools for participation of stakeholders and conflict management and forms of co-operation;
5. Communication, feedback of the outcome and capacity building;

The proposal is to formulate a project plan for organisation, research and demonstration of sustainable water management in the Pantanal in close co-operation with the groups involved in the region. EMBRAPA-Pantanal proposes to develop a river basin approach for the Rio Taquari including land use activities in the Planalto. In this approach a study should be done to the hydrological ecological land use developments and development of an integrated approach towards sustainable use. One of the options is the dredging of parts of the Taquari to restore river discharge. This however is only a good investment within the framework of a river or catchment management plan. Another option is the establishment of a national park in the flooded area, but also then knowledge of the hydrological processes in time and spaces as well as the consequences for the users should be known.

The Dutch contribution in the water for ecosystems programme will be 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. Hotspots for biodiversity are being identified and together with the regional stakeholders the management of the river basin will be set up. 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.

The role of the Technical Commission of the Taquari is essential in the project, because they form the future basis of sustainable management. It is important within the project to establish a knowledge basis and develop the attitude within the commission on sustainable objectives and participation. Through this commission the blue agenda of the Programa Pantanal must be established and the commission and its future work should be the example for the set-up of other commissions in the Pantanal and elsewhere in Brazil.

1.2. The Pantanal and the river Taquari

The Pantanal (85-180 m 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. It comprises an area of 496,000 Km^2, being 396,800 km^2 within Brazilian borders and the remaining section in Bolivia and Paraguay (99,200 km^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 800 km. 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 29,000 km^2. The total area in the Pantanal is about 50,000 km2 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 smaller 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).

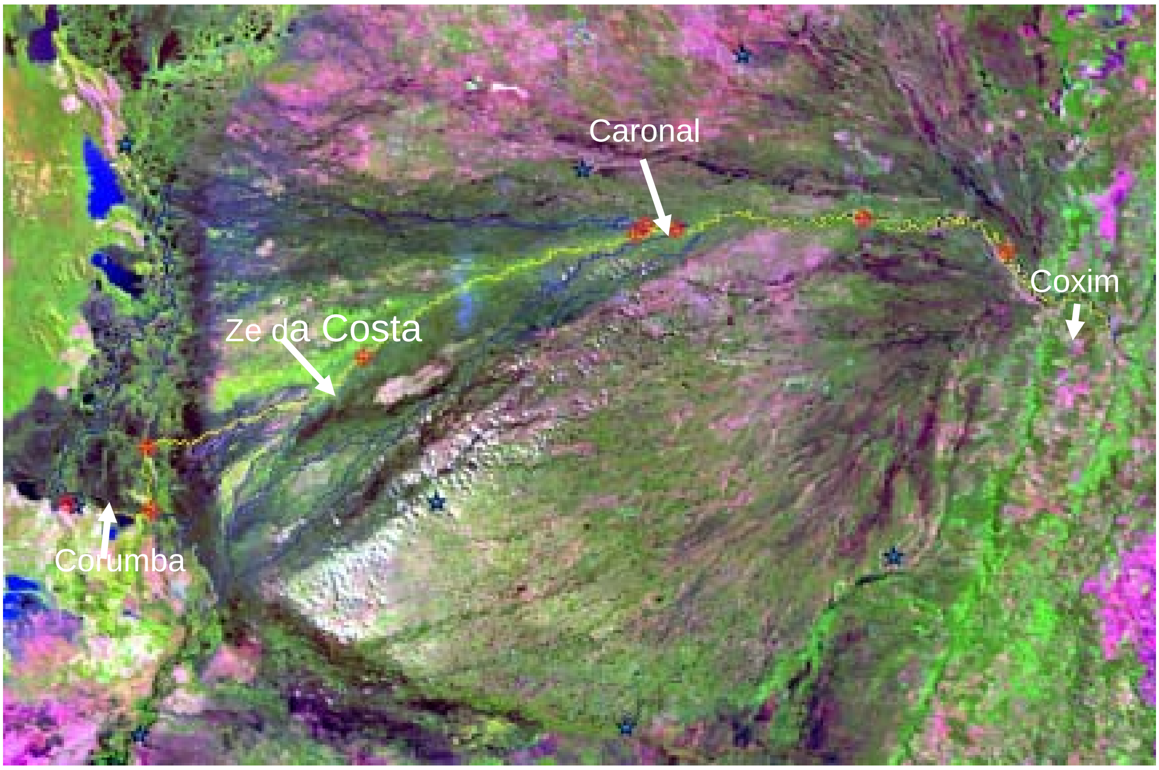


Figure 1.1. The Rio Taquari in the Pantanal, with the major towns (Coumbá and Coxím) and avulsions (Ze da Costa and Caronal).

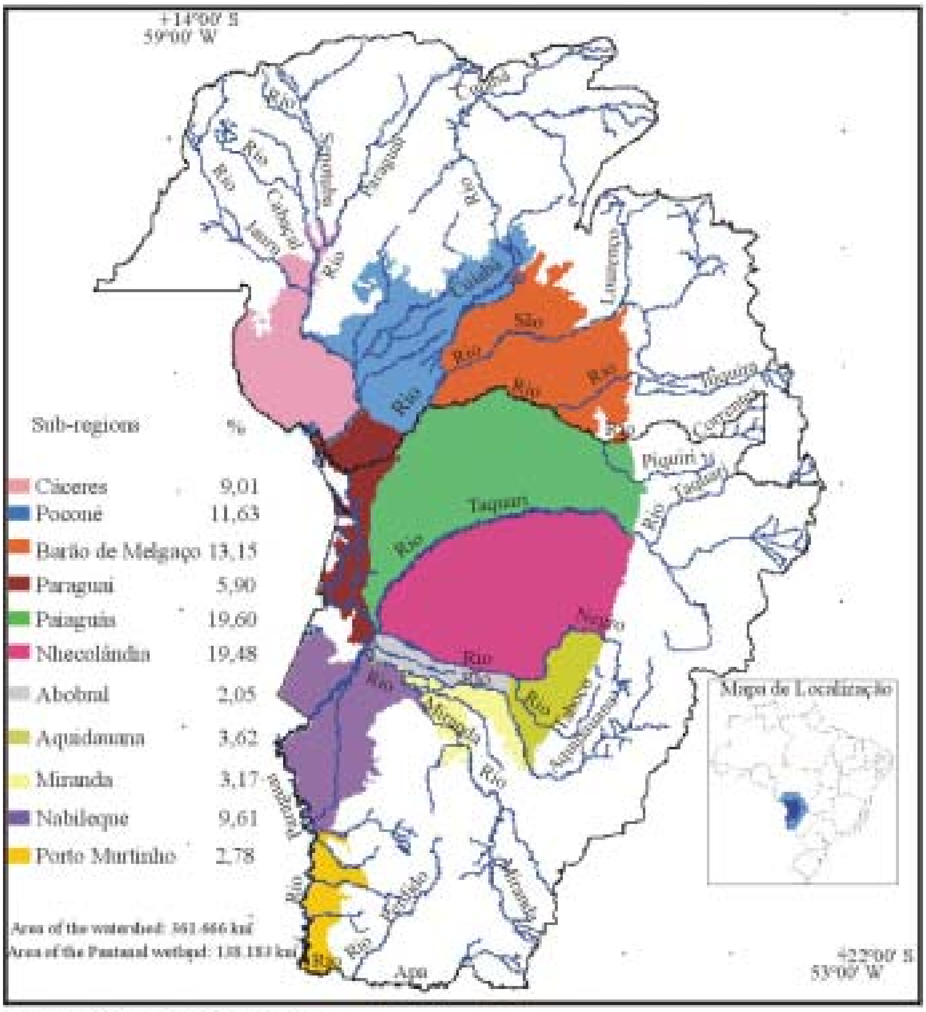
The Coxim and Jauru Rivers are the main tributaries of the Taquari and they represent with the upper reaches of the rio Taquari one of the major erosive areas of the highlands around the Pantanal, consisting of sandy soils. This erosive character has resulted in an inundated area of 11.000km2 in the lower reach of the Taquari, more or less downstream of Caronal (Figure 1.1).

The inundated area is between the old bed of the Rio Taquari and Corixão in the north. In the upper Taquari the area quartosa (arenosa) is about 13,380.08 km^2 (45.72%). The loss of soil is high in 12,603.75 km^2 (44.3%) of the total area of 28,450.90 km^2. The yearly average potential loss here at present is 555.61 t /ha (Figure 1.2; Figure 1.3). Here a considerable change has taken place in local land use The sediment discharge at Coxim was in 1995 2000 m^3 per day.

Figure 1.2. Local erosion on the Planalto

Figure 1.3. Erosion gully on the Planalto

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 (Cadavid Garcia, 1986) do not seem to be economically viable any more. 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 relates to the state of the environment: there is a decline of important plant species and intoxication of fish by agrochemicals (water is everywhere) birds and alligators (jacaré).



Fonte: Silva e Abdon, 1998
Figure 1.4. The major rivers in the Pantanal

The Pantanal in Brazil consists of a number 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 100 km 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 several ancient parts characterised by a precipitation dependent system of baías and salinas (Figure 1.7, Dantas et al 1999, Assine and Soares, 2003). In the wet season streams link most of the waters with each other through corixos (permanent linking channels) and vazantes (temporary water channels often in old river beds, Figure 1.8). In the wet season large areas of the savanna are flooded (Figure 1.9).


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


Figure 1.6. The Rio Paraguay with its floodplains

Figure 1.7. Baías and Salinas in Nhecolândia.

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

Figure 1.9. Flooded grassland savanna (savanna lenhosa)

1.3 The environmental problems of the Taquari

Erosion and silting up make the major rivers of the Pantanal and especially the river Taquari into unstable braiding systems 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 of the Planalto since the early 1970s. The sanding up of the Rio Taquari is at the moment a major problem in the Pantanal and of Mato Grosso do Sul, because of the nearly permanent inundation of an area of about 11,000 km^2 in the sub-regions Nhecolândia and Paiaguás. There is pressure from different sides to take action varying from requests for making a national park to damming and dredging the river. However, there is no coherent river management system and the behaviour of the river, especially in the lower reach is unknown. The knowledge to tackle both problems is lacking and should be required from outside.

A preliminary study showed that possible causes of the changes in the river system are not well known, but can be both natural and man induced:

4 Natural river processes

4 Climate change Ÿ increased precipitation:
  - o Increased erosion and sediment transport
  - o Changes in vegetation: increase in superficial and subsurface flows

4 Land use changes and related vegetation changes (Figure 1.10)
  - o Increased erosion and sediment transport
  - o Changes in discharge patterns due to drainage
  - o Changes in vegetation: increase in superficial and subsurface flows

4 Incorrect river management

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

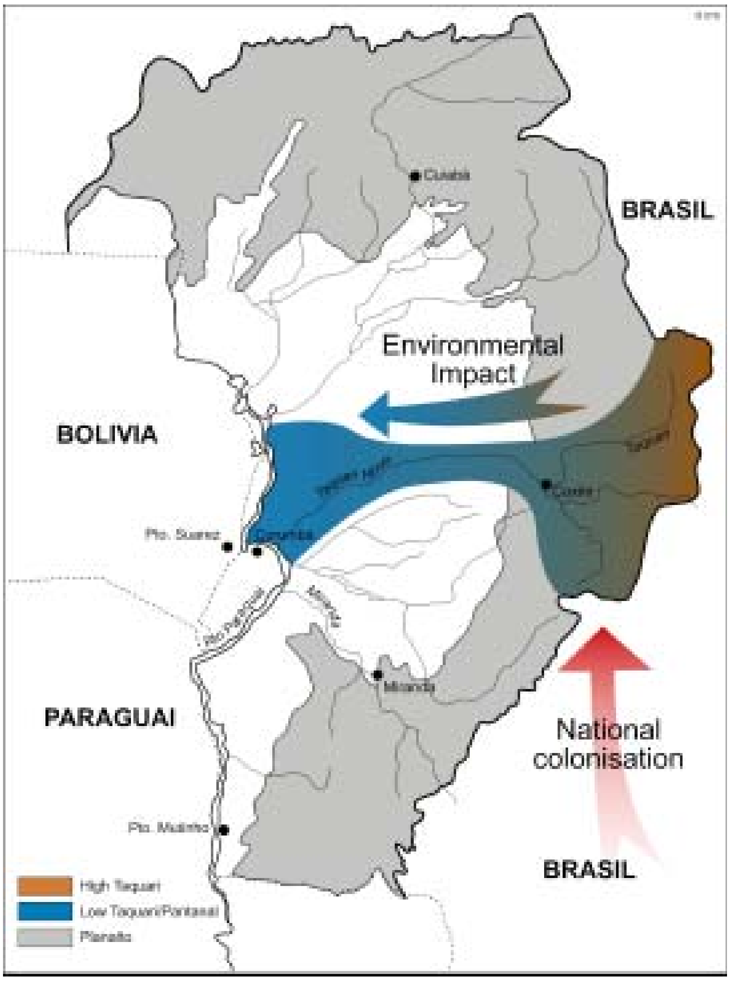


Figure 1.10. Supposed relationship between demographic and environmental impacts in the Taquari Basin.

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.

1.4 The approach

Along its course, every river changes its ecological structure and function. The concept dominating the 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 energetics 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:

1. Longitudinal links along the length of the river system, such as the river continuum (Vannote et al 1980), downstream barriers to migration
2. Lateral links with the adjacent terrestrial system, such as the flood pulse concept (Junk et al 1989).
3. Vertical links with and through the riverbed (Hyporheic corridor concept, Stanford & Ward 1993)

The lateral and vertical dimensions of the ecosystems need to be 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 strategic integration of river management and farming (as well as other socio-economic activities like tourism) with biodiversity conservation in the Pantanal. It is based on existing knowledge, but it also identified gaps in knowledge and filled these gaps through research and improving scientific and planning capacities in the region. A common approach has been developed in research, scenario building and policy and management development. The project EMBRAPA projects on the alluvial part of the Taquarihave been integrated:

- "Evaluation of the flood dynamics of the Taquari fan using GIS and remote sensing to the management the natural resources" with the objectives to
- Long Term Ecological Project (PELD), a ten-year project monitoring floods in all Pantanal area using AVHRR/NOAA images. The objectives are:

2 Flooding and sedimentation on the lower Taquari River; a geomorphological study of its causes

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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 Paraguay 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. Complementary reports dealing with channel-scale processes and hydrological modelling are prepared by WL/Delft Hydraulics and Alterra.

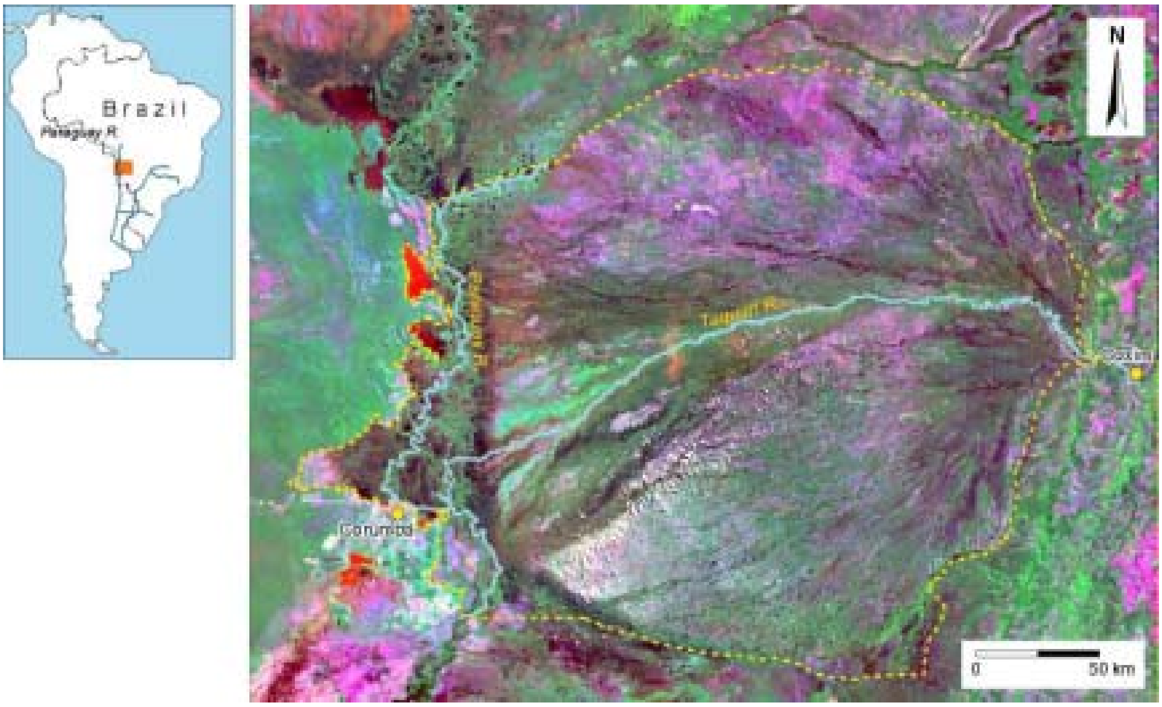

Figure 2.1 Location of the study area

2.2 General characteristics of the study area

The Taquari River is a tributary to the Paraguay River (Figure 2.1). Where the Taquari enters the Pantanal lowlands, its mean annual discharge is around 400 m^3/s [period since 1973 (Galdino et al., 1997, Padovani et al., 1998a)]. Taquari discharge is highly seasonal with mean peak discharge around 1100 m^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 250 m^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 100 km. 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 150 km long. In its lowermost reach, the Taquari River flows for 25 km across a low-gradient floodplain that seems principally built by the Paraguay River.

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 often occur in semi-arid climates, 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 250 km 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 fan’ as defined by Stanistreet & McCarthy (1993). 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.

Climate in the study area is humid, with spatially variable yearly precipitation in the area roughly ranging from 1100 to 1800 mm (Galdino et al., 1997). Rainfall is markedly seasonal: December and January are the wettest months with average monthly precipitation well over 200 mm in most of the area, whereas July and August are dry with average monthly precipitation mostly below 30 mm. 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 the alluvial fan, aggradation is strongly localized and almost exclusively occurs 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

The channel that feeds the active lobe with sediments and water, often is incised in the upper parts of the fan (Fig. 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 (cf. 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 (Fig. 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.

2.4 Geomorphological 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). As to the older forms, 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, awaiting 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 2.2). 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 predates 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.

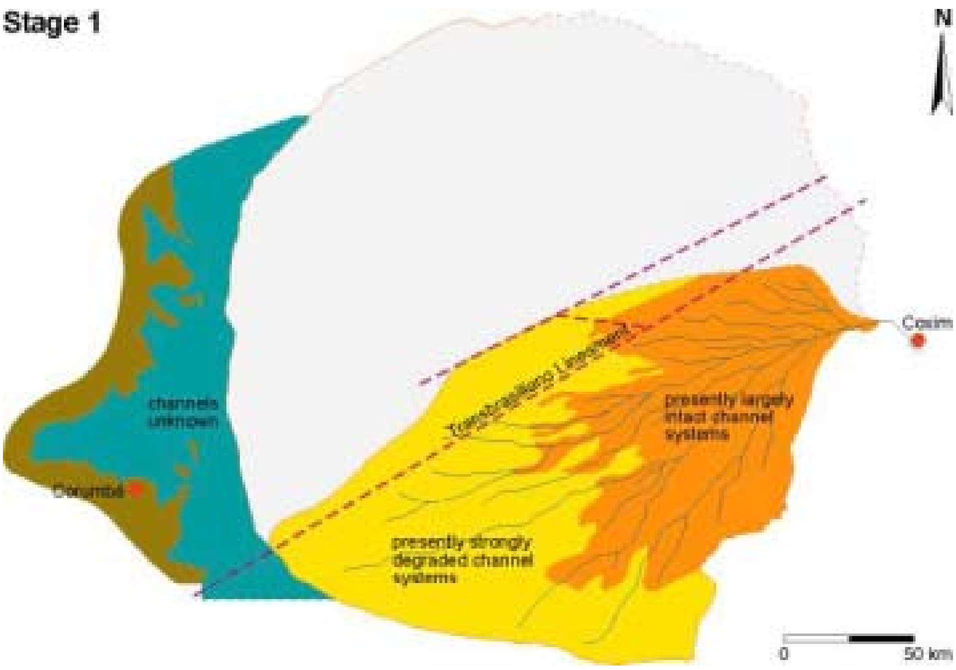

Figure 2.2 Oldest formation of the Rio Taquari in the Pleistocene-Holocene transition period

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 (Fig. 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, formations of such duricrusts takes several thousand years, at least.

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 (Figure 2.3). It is speculated that the inability of the degraded channel systems on the southern fan to cope with increasing discharges were 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, creating a favourable gradient may have 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.

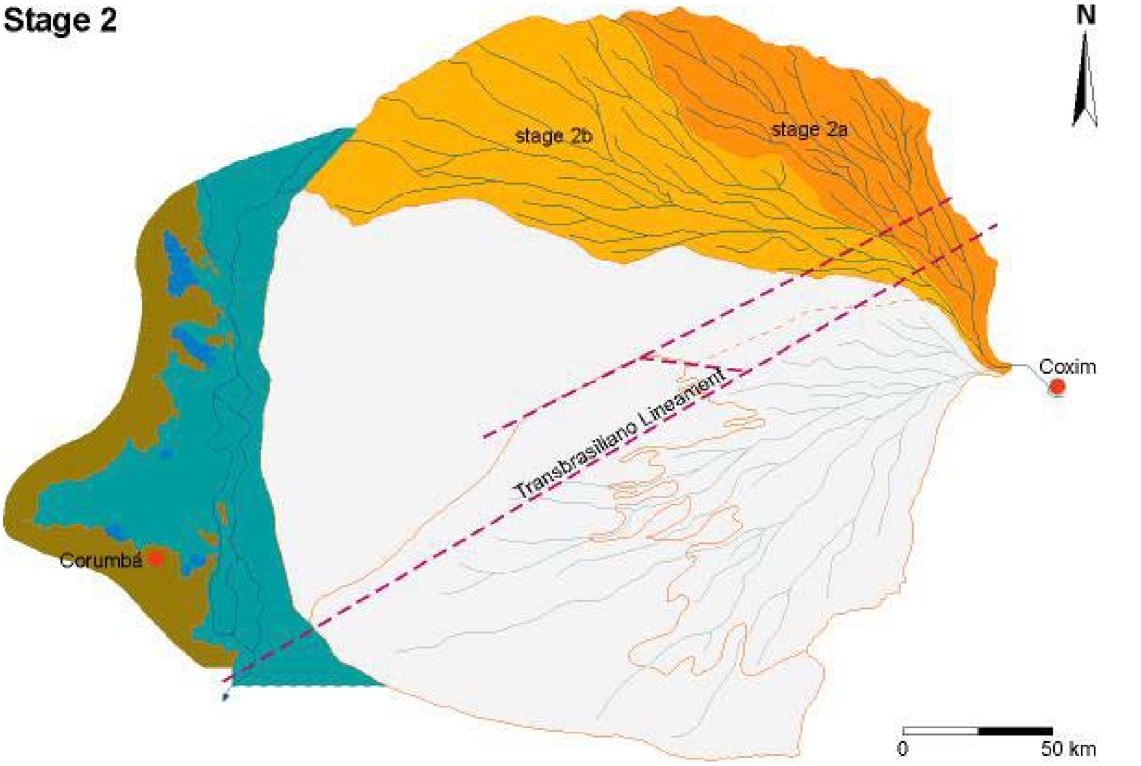

Figure 2.3 The Taquari during the early Holocene

Rapid aggradation of the first northern fan lobe resulted in the development of progressively steeper gradients in a west-northwesterly 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 (Figure 2.4). 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.

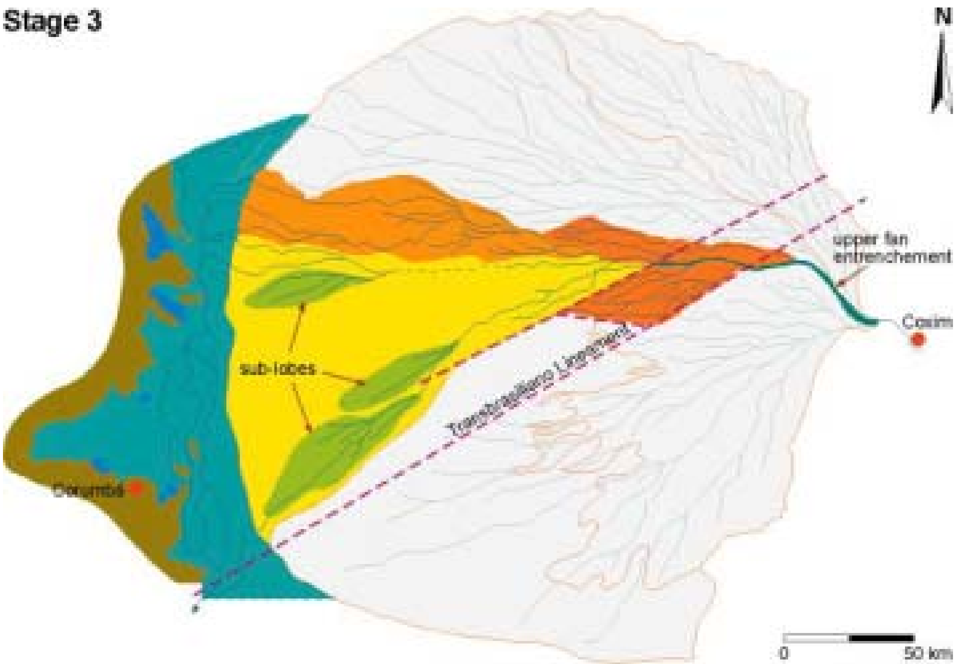

Figure 2.4 The Taquari in the Middle Holocene

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 2.5).

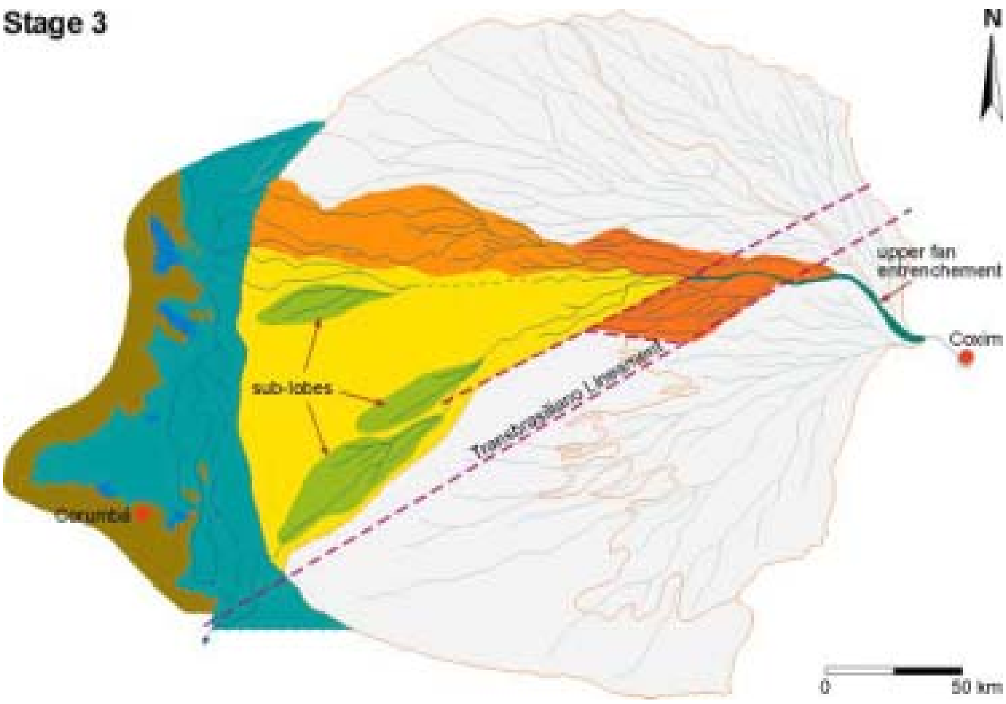

Figure 2.5. The Taquari in the late Holocene

Active fan lobe and Paraguay River floodplain

Within the present active lobe, a number of channel belts and associated sub-lobes can be 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. Morphologically, these old channel belts already become poorly defined and start to blend into the surrounding floodplain by ongoing sedimentation of 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 presumably overlapped with the period of formation of the fan lobe north of the present active lobe. In this 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 in the present active lobe. 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.

A big avulsion near the apex of the presently active fan lobe led to establishment of the present upper reach of the Taquari, within the present active lobe (Figure 2.6). 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.

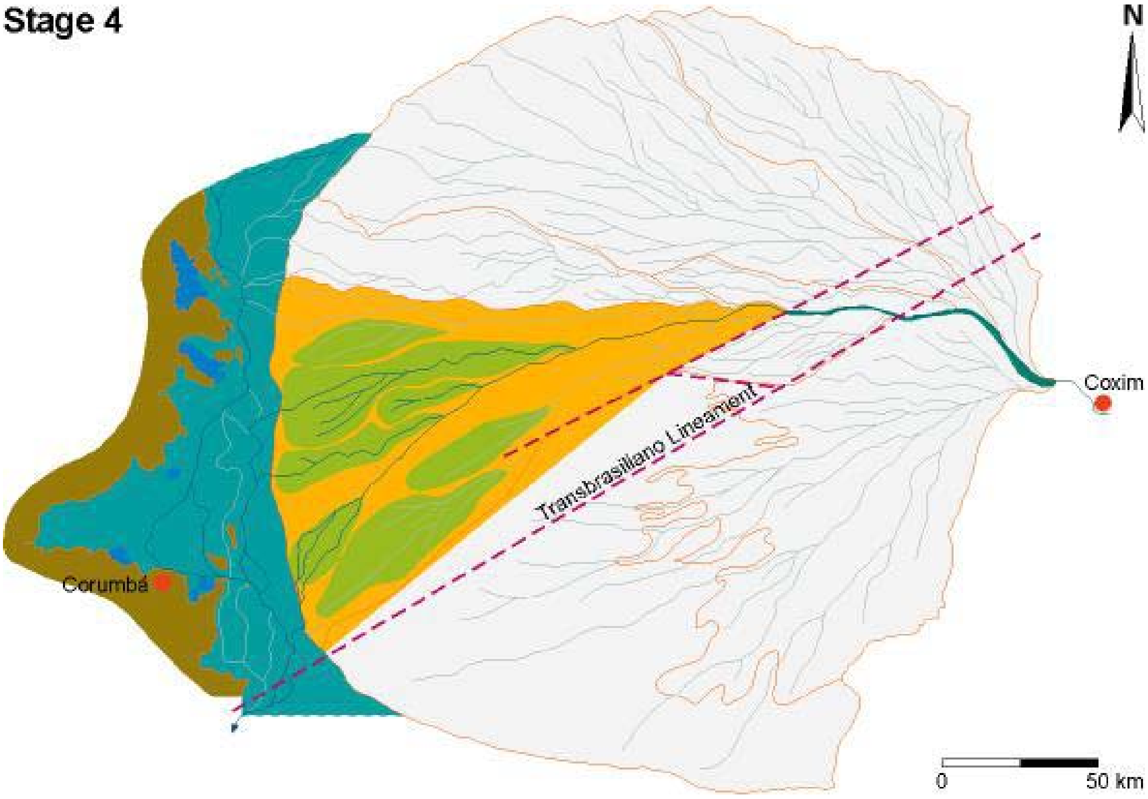

Figure 2.6 The present active lobe

The westward shift of the Paraguay River to the Corumbá area may be related to a rise in floodbasin water levels east of the river, due to increased discharge through the present active lobe. Likewise the Rio Cuiaba 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. The new course of the Paraguay River crosses the abandoned old Paraguay channel belts east of Corumba and probably linked up with a lower course of the Taquari.

Presently, new avulsions are taking place in two areas (Figure 2.7). In the middle fan area, near the apex of the presently 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 follows 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, topographically, which probably explains that the avulsion has rapidly developed since 1979 (the year of its initiation, according to a local farmer). The old 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 (Fig. 12). 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 (Fig. 13).

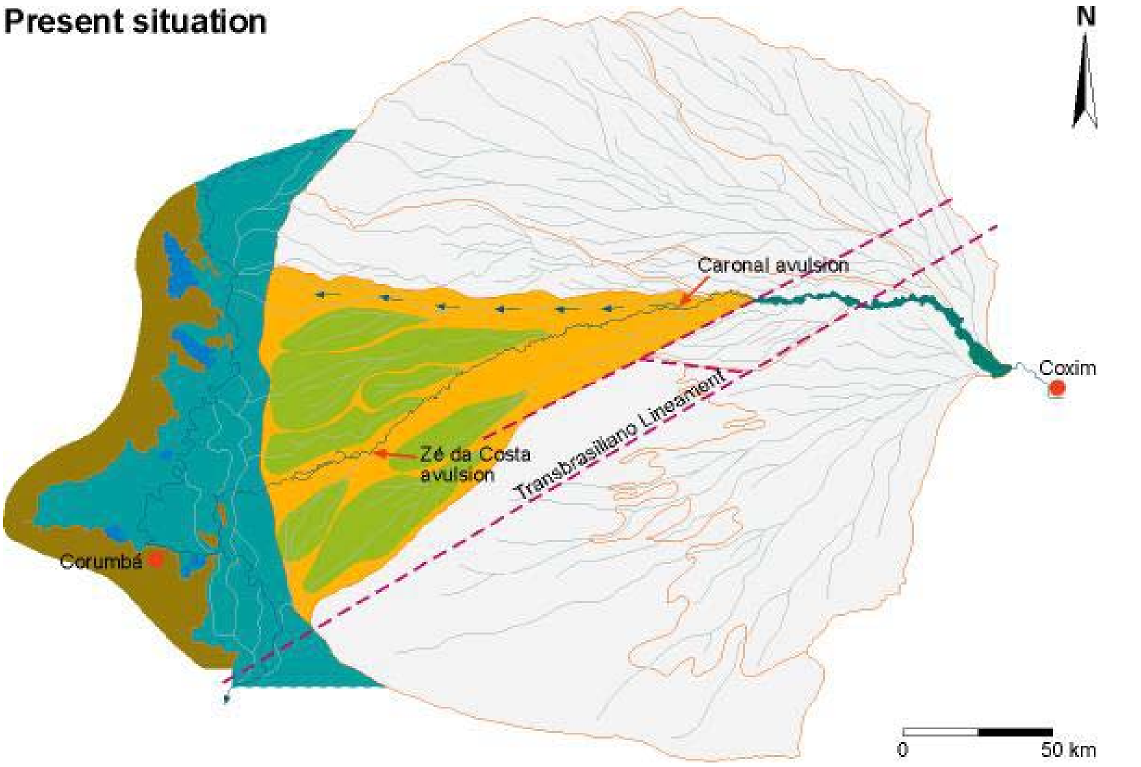

Figure 2.7 The new avulsions in the Taquari at Xe da Costa and Caronal.

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, but 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, probably 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 causes, timing and locations 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 causes, the exact locations and the timing 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 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 serves as 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. Many 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 probably not be accommodated by the present Taquari bed. Confinement of the Taquari floodplain on the upper fan 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 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. 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 may create low spots in the banks that are suitable avulsion points.

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 'modern' (post 1950 AD) radiocarbon dates. It should also be stressed that these sedimentation rates probably refer to a very local situation and partly may reflect in-channel sedimentation related to lateral channel migration, which is much more rapid than overbank sedimentation. Nevertheless, the sedimentation rates, if true, 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 and was 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 more or less 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 the 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 most likely 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. 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, 20 km 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 presently 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). It is unclear whether they represent overbank sedimentation or in-channel sedimentation.

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 the report by Chris Stolker (Delft Hydraulics)]. This may trigger avulsion and, once initiated, may contribute to rapid further development. 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 floodlevels 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, remarks 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 caused by climatic change.

5. The Zé da Costa avulsion is probably strongly 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, 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 advantageous. Recurrent avulsions rejuvenate vegetations, create landscape diversity and thereby probably 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

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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 Brasilian knowledge in this matter. Second is the capacity building for the organization of integrated river management at the catchment level including all relevant stake holders. 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 modeling by other partners.

3.1 Outline of main activities

1. Remote sensing data collection, initial analysis and preparation of presentation.
2. Participation in the 1st workshop on the Taquari-Pantanal Project, Corumba, 19-20 August 2003. A presentation was given entitled: Remote sensing image analysis and altitude determination of Rio Taquari-Pantanal system (appendix 1).
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 modeling (appendix 2).
5. Participating in a joint fieldwork in April 2004 to collect additional data on the Taquari river from Coxim to Corumba using several techniques.
6. Processing the collected data and presenting the obtained results in a presentation at Alterra entitled: Pantanal Digital Terrain Model (appendix 3, 4).
7. Disseminating the processed data to Alterra.
8. Preparation of a poster presentation showing the obtained results for the closing workshop in Corumba (appendix 5).

3.2 Outline of main in-house activities

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.

3.2 Data collection and processing

Prior to the first workshop most attention was given to data collection.

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 analog 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 analog archive were available (covering small portions of the Paraguay 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 30 m. 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 100 m. 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 60 m. 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 90 m (3-arc-seconds at equator is 90 m), which is downsampled using a 3 by 3 averaging filter algorithm from the original 30 m. 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 is provided below.

Data collected at Embrapa in August 2003

After the 1st workshop at the Embrapa office in Corumba 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 180 m.
- A mosaic of Landsat TM, representing the dry season conditions as of 1998-1999, transformed to a pseudo natural colour, in 30 m. and 180 m. 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 savanna vegetation. Only along the escarpments a dense forest cover is located. Given the type of land use and cropping patterns for the area in relation to the date of acquisition, nature of interaction at the surface given the wavelength used of the active radar signal to collect the elevation information is 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. Examples of these compound index maps are provided in appendix 1.

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 and is discussed into more detail below:

1. 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.
2. 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 color 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

3. 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 the given sequence) completed the initial DEM correction procedure. 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 considered still 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. A presentation highlighting the proposed modification procedure is given in appendix 2.

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 Corumba 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 Caranal and Ze da Costa avulsions.
- Collect multi temporal aerial and satellite image info for change analysis along the sections affected by avulsions.

Equipment used for survey

1. Leica SR530, RTK (D)GPS and antenna
2. Garmin Fishfinder – transducer (sonar) and Garmin GPS 72
3. Garmin Etrex GPS
4. Laptop (Erdas Imagine, ArcGIS, Arcview, ILWIS, Leica-SKI-Pro and Gartrip) and a palmtop (Ipaq with ArcPad)

The data collected:

1. Sounding and GPS information along the river, the whole section, from Coxim to Corumba, water depth, height and X,Y (UTM, zone 21, WGS84) information, longitudinal profile, 1 point per 10 seconds (approximately 1 point per 80 metres), 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 Merin, a point at Corumba harbour, 2 observations on geodetic points at University of Corumba, one from the aviation authority and one from the Department of Geodesy, Brazil (IBGE). Time duration per point between 1 ½ 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 (+ 30 cm) and GPS height offset (- 60 cm). General overview of data collected is presented in Figure 3..1 (total river length covered: >400 km.). Sediment samples (17) are given to the laboratory of Embrapa for grain size analysis. Further details are presented below.

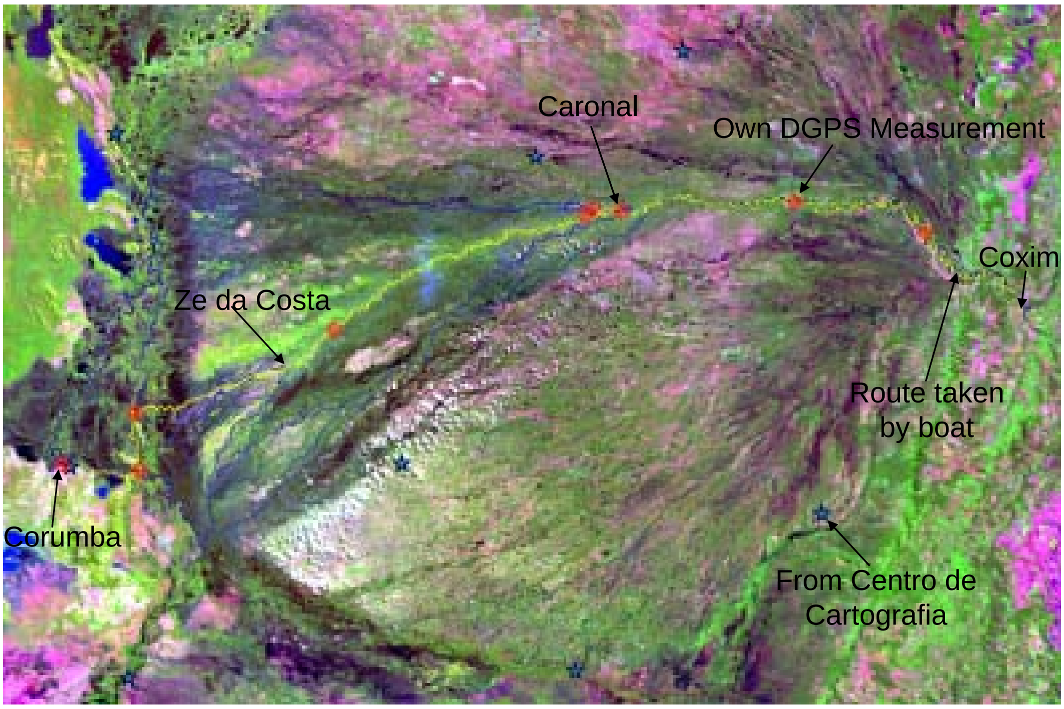


Figure 3.1. Track record and (measured – obtained) DGPS locations along the Taquari.

When plotting all data on pseudo natural color 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 (Carlos Padovani) 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 Corumba, a transducer – sonar was attached to the back of the boat, about 30 cm below the water level. Water depths are registered using this portable sounder connected to a GPS. The sounder uses a single frequency transductor of 200 kHz to measure the distance from the sensor to the river bed with an accuracy of 10 cm. Minimum recording depth of the water body is 60 cm. 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 10 m. 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 10 km) 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 Jianero 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 50 cm. Therefore use was made of a free Internet GPS post-processing service provided by the Scripps Orbit and Permanent Array Center (SOPAC). This center 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 Corumba, Brazil. This resulted in height differences of 2.5 cm (average base line of 130 km) and 11 cm (average base line of 1160 km) for Enschede and Corumba 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 Corumba, the obtained vertical accuracy (in the order of 10 cm) 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 30 km east of the Caronal avulsion. The Taquari incised the fan surface, is confined to a narrow active floodplain, with levees of about 60 cm 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 6 m. 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 30 cm / km and the river depth in general is exceeding 2.5 m. Furthermore the river width in general is greater than 300 m. 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 1.5 m. 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 30 km 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 30 cm above the water level. Hardly any signs of river bank (lateral) erosion. The width of the Taquari decreased to less than 200 m. The river depth is in general less than 2 m. The longitudinal slope in this reach is between 20 to 30 cm / 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 4 km / hr but still suspended sediments are transported. In general flood marks are situated 10 to 20 cm above the levee surface adjacent the river indicating that large regions are flood affected during high river stage.
- Downstream Ze Da Costa avulsion. Here the longitudinal gradient becomes very gentle, about 10 cm / 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- 2 km / hr. In general the surveyed reach is having river depths of over 3 m. 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 the 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 is at maturing stage, about 20 cm above surface. At local places, 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 10 mtr high, some trees locally more than 15 mtr. Natural vegetation (deciduous) on the fan surface is open and generally lower, about 5 to 10 mtr. 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 0.5 mtr 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 actively growing making it difficult to determine the actual river bank. At localized higher portions (e.g. fossil levees which are found extensively 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 600 meter 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 al 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.

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

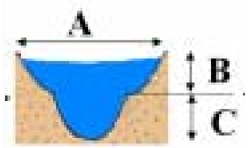
The difference given for the first measurement is most probably due to the spatial resolution of the SRTM data. The DGPS measurement was conducted next to the river, about 30 m from the fan. The SRTM value is typically representing the altitude fan surface at that location. Largest deviations occur downstream with measurements conducted along the Paraguay Merin. 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.

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). 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 colored 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 of run 3.

Figure 3.2: Drainage optimization parameters used

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

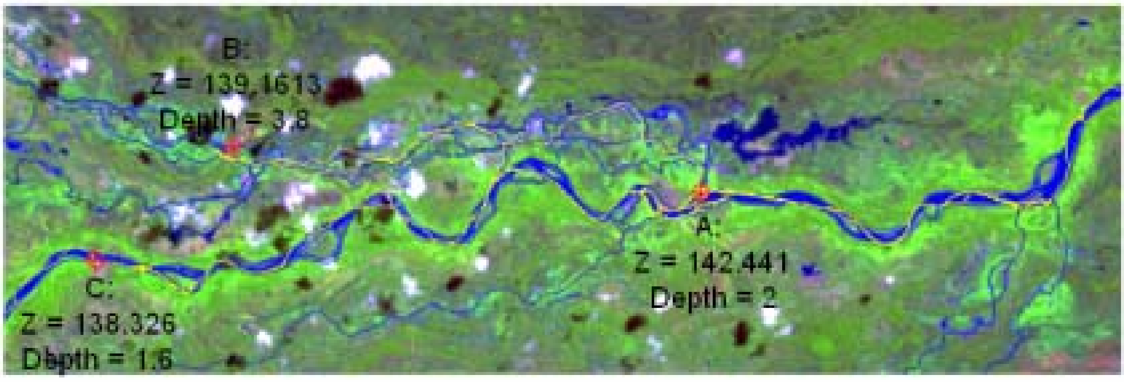


In order to obtain a hydrologically consistent DEM (water is draining to a specified outlet) first possible pits are filled in the DEM (no internal drainage). No control over the fill pit routine was applied resulting in the fact that e.g. a closed depression existing in the DEM would be removed and is “leveled” 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 Ze 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 6 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 60 cm. 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.

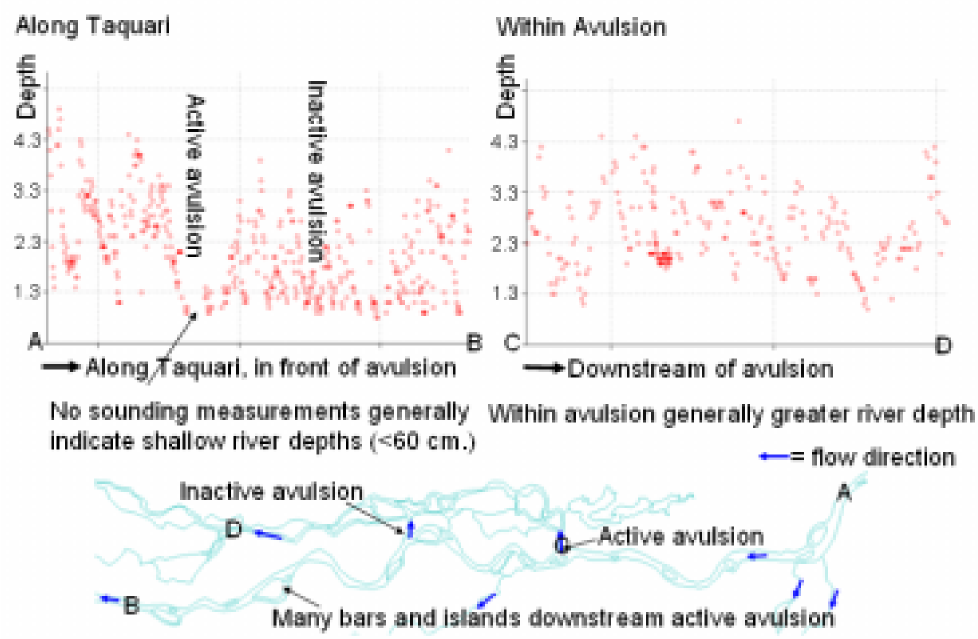


Figure 3.4: Sounding measurements Taquari and Caronal avulsion

The drainage layout presented at the bottom of figure 3.4 shows the present drainage layout 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 into more detail what are the reasons 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.

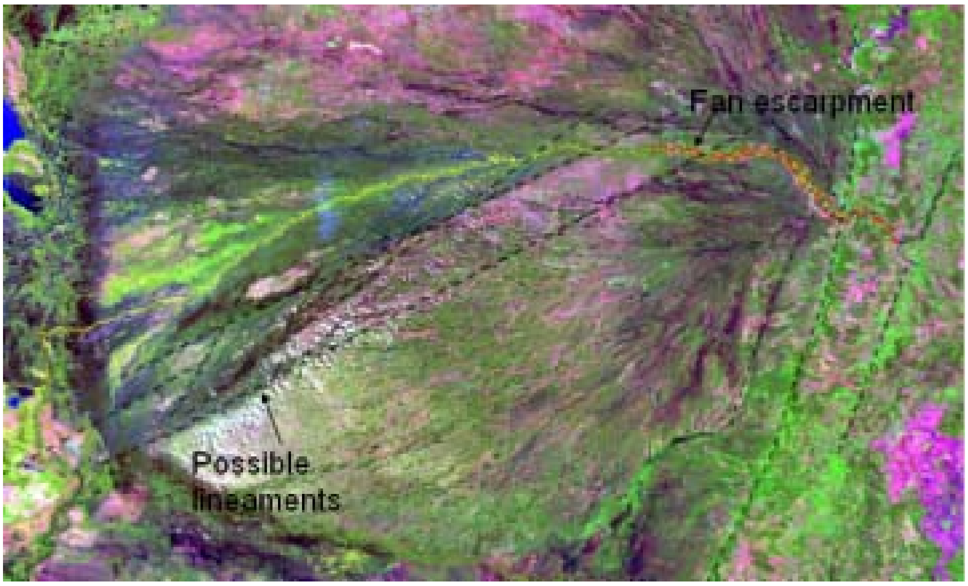


Figure 3.5 Lineaments identified crossing the Pantanal region

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 meandering tendency, 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 neo tectonic 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 3.6using 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.

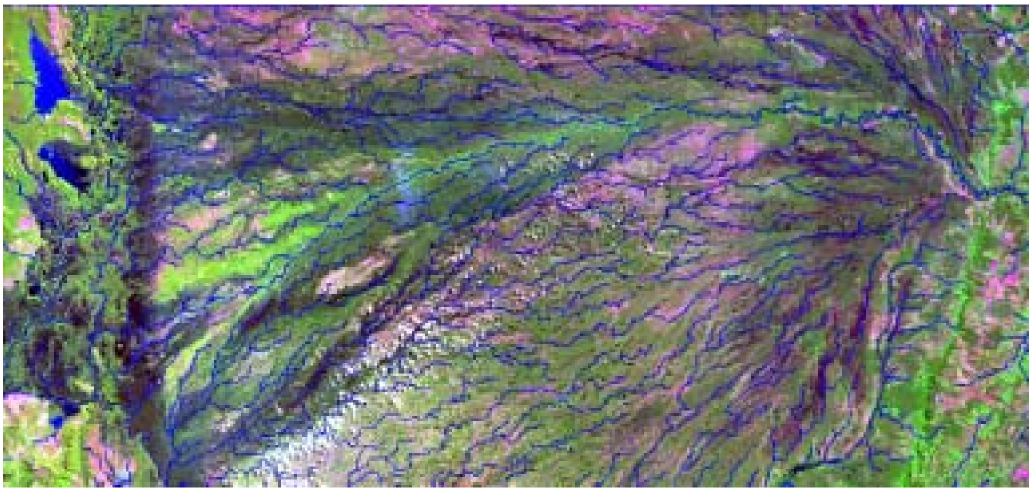


Figure 3.6: Extracted drainage

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 color (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.

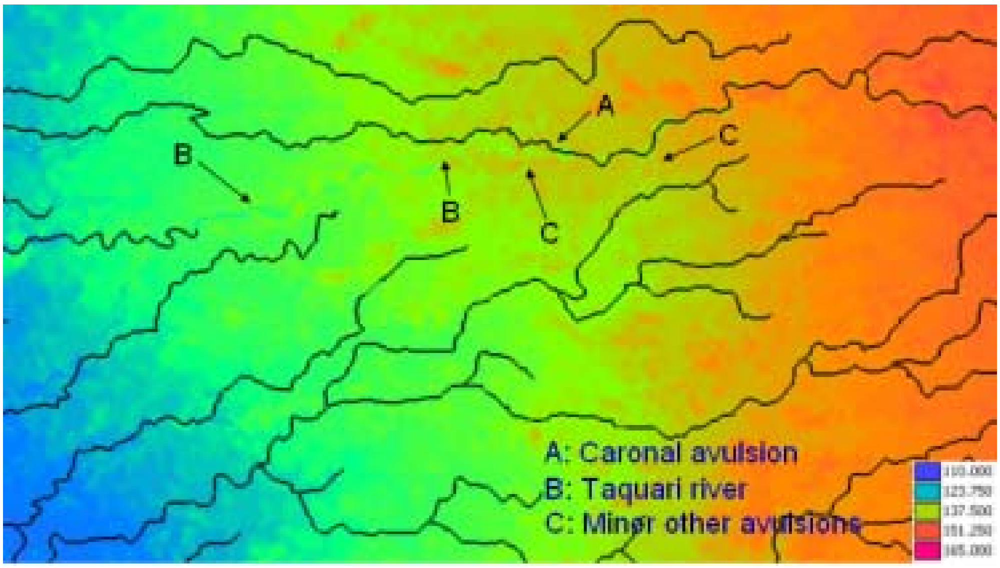


Figure 3.7: DEM of the Caronal region

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

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.

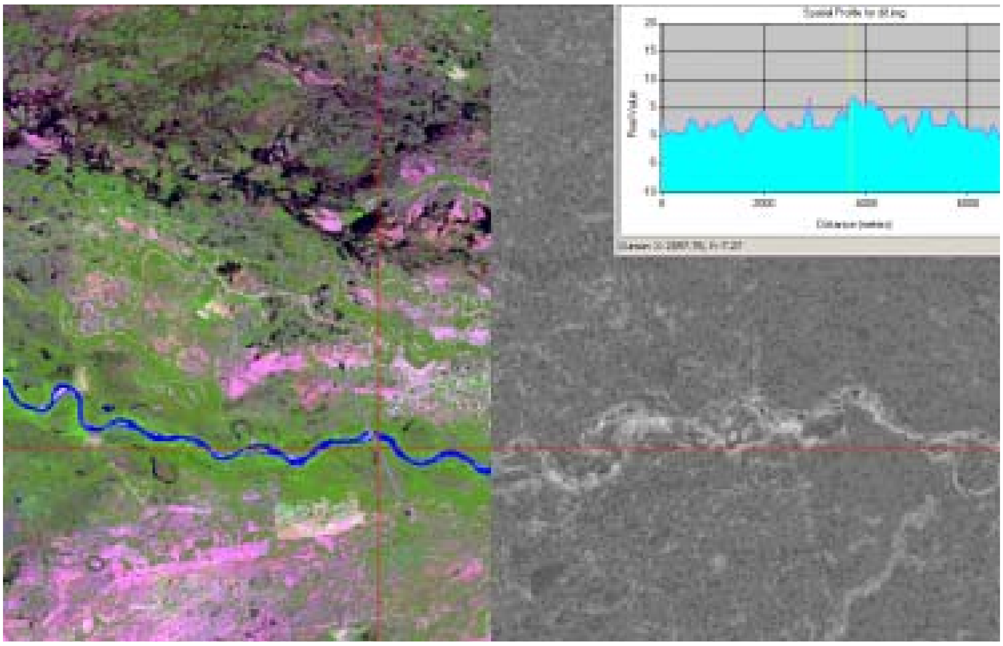


Figure 3.8: DEM difference map and satellite image window

The difference map displayed in gray 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.

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 is clearly showing the effects of the drainage optimization used. The riverbed is approximately 2.5 to 3 m 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 20 km long section, from the uplands (south-east of Corumba) 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.

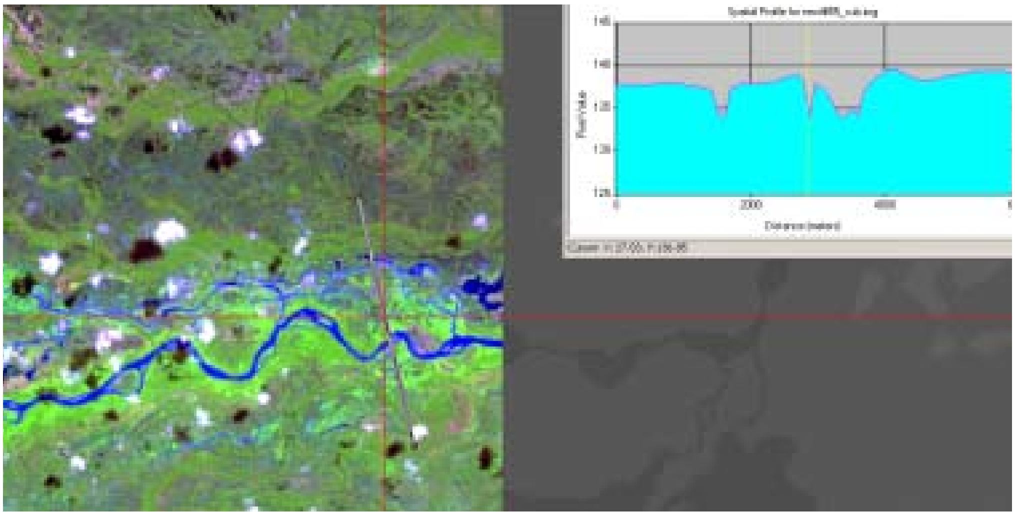


Figure 3.9: Processed DEM and satellite image window Caronal avulsion

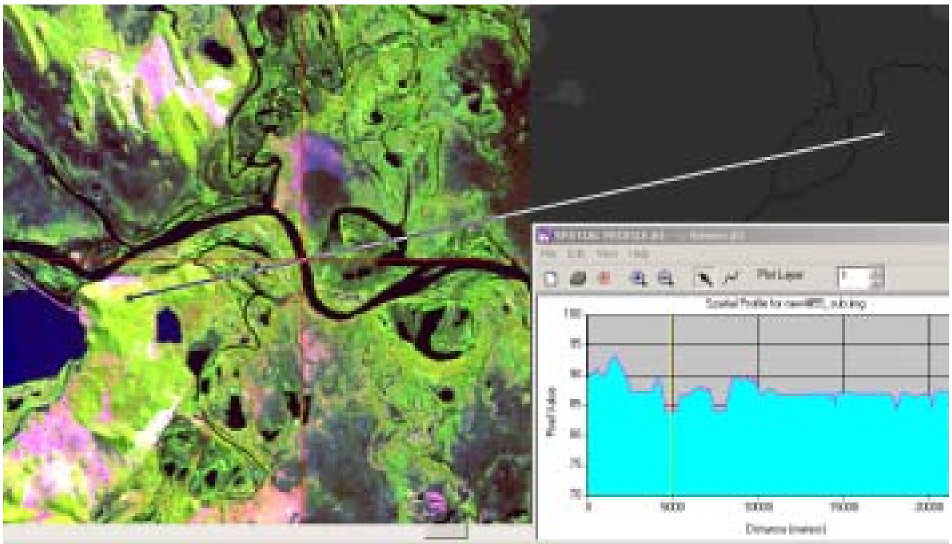


Figure 3.10: Processed DEM and satellite image window Paraguay floodplain

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 a 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.

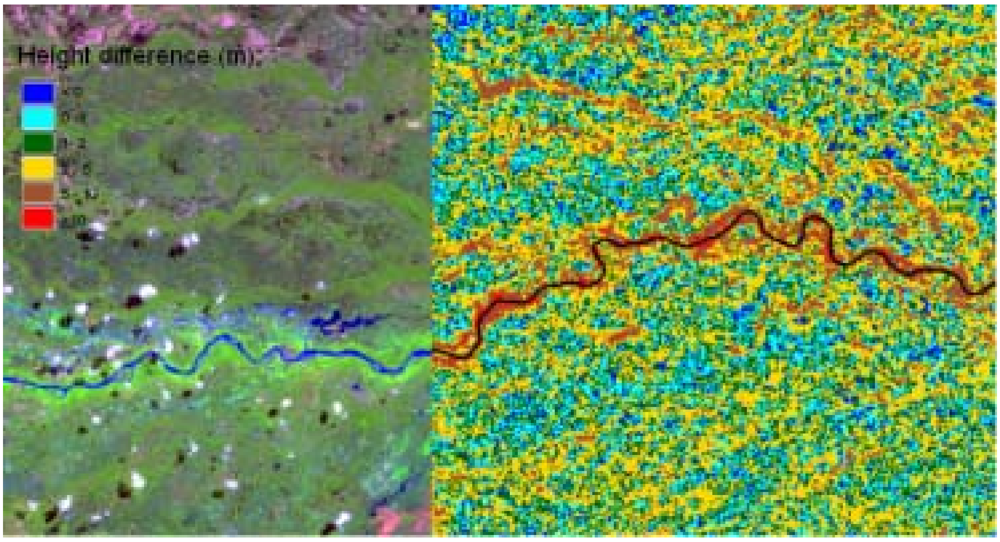


Figure 3.11: Spatial distribution of elevation differences computed

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 this work presented a number of conclusions may be drawn with regard to the 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 10 meters, 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 Ze 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, Marcel Ververs, Balbina Soriano, Sergio Galdino

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

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. 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.

Also Balbina Soriano and Sergio Galdino made an important contribution to this research. They were responsible for collecting the meteorological and hydrological data respectively. Whitout this data the two dimensional hydrodynamic SOBEK model could not have been accomplished.

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 dbasic 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 Agéncia Nacional de Águas (ANA) through its website supplies data in a typical 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 4.1). The conversion tool can also create an import file for HYMOS

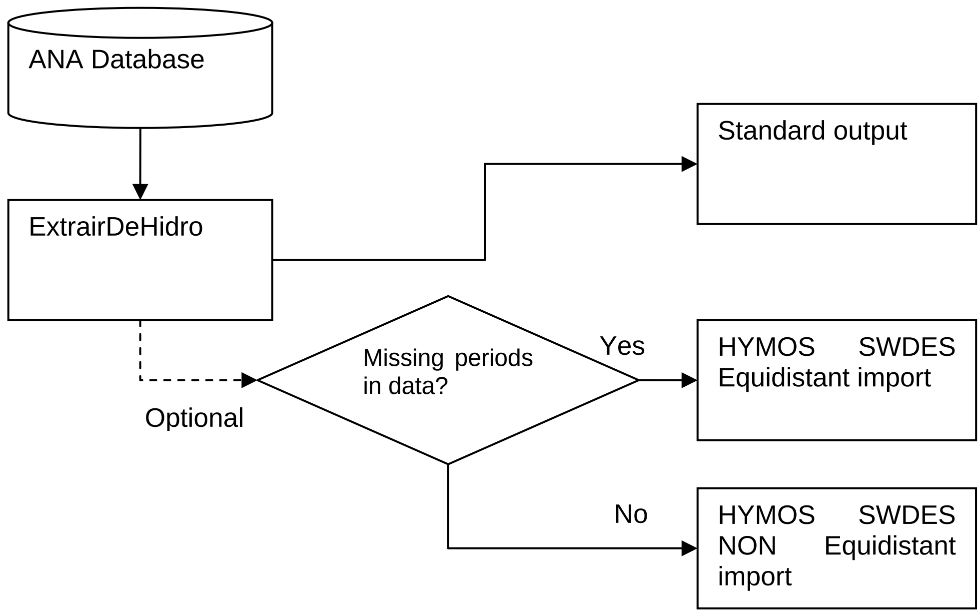


Figure 4.1 Conversion of ANA data into HYMOS

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.

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

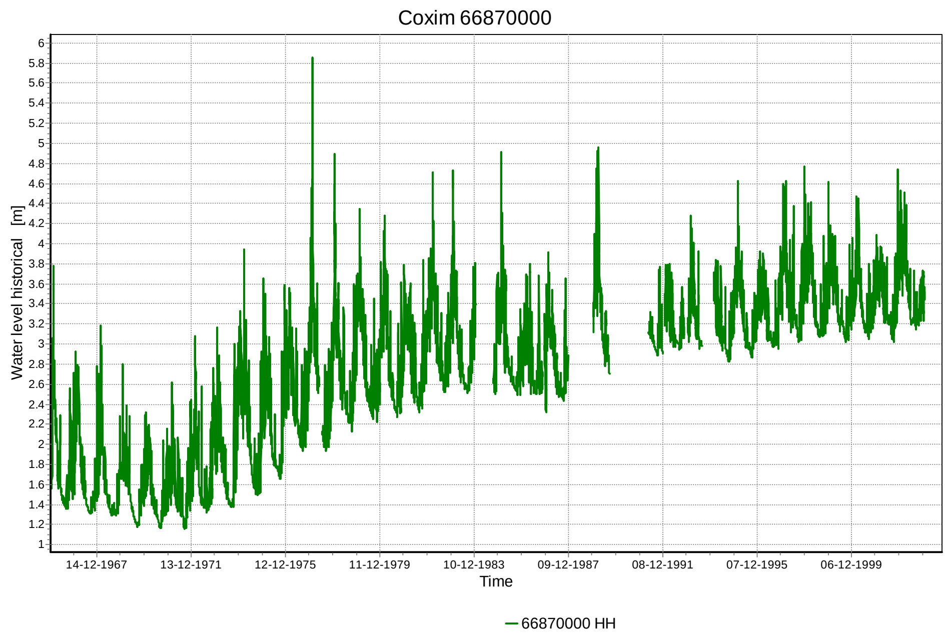


Figure 4.2 : Water Levels at Coxim

Figure 4.1 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.

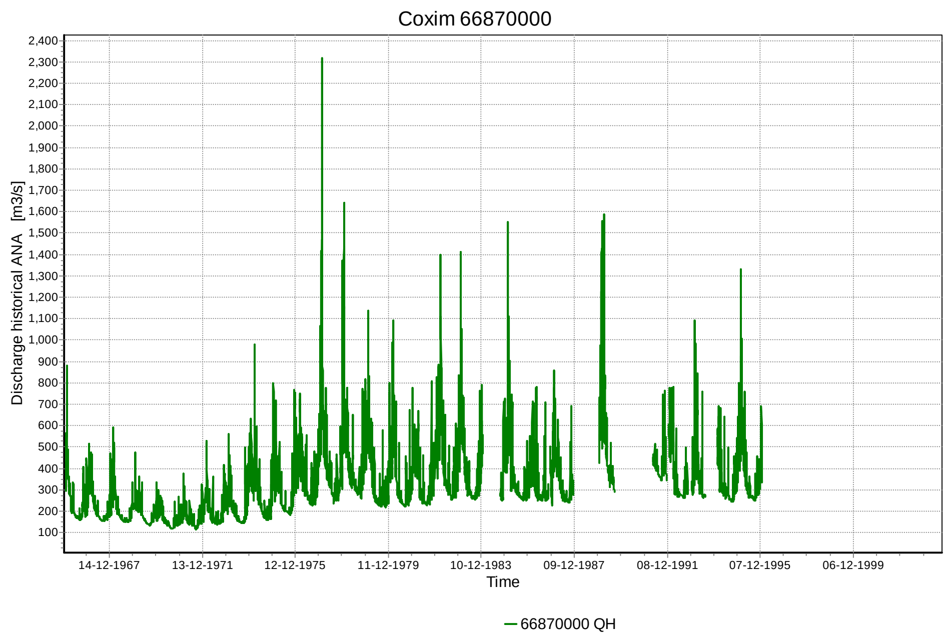


Figure 4.3: Discharge at Coxim

Figure 4.3 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 4.3 has been made using the exact same time scale as Figure 4.2. Discharges for the required period of 1999 - 2000 are not available.

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.

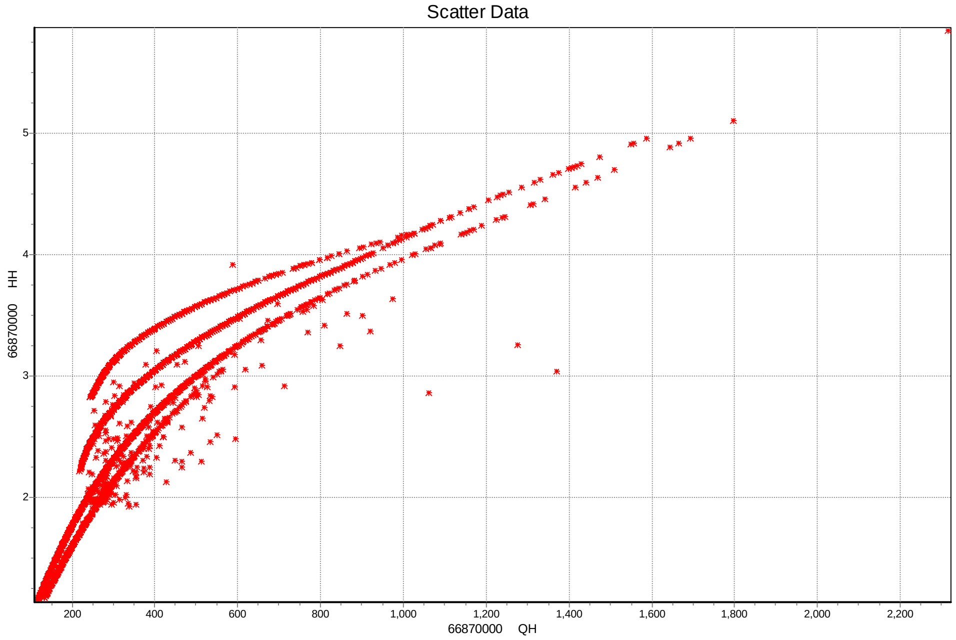


Figure 4.4: Scatter plot of Water levels (Horizontal axis) plotted against Discharges (vertical axis): 1966 - 1995

Figure 4.4 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 Jan 1966 to Dec 1995 the shift indicates a raised bed level of approximately 1 meter.

The final rating curve is presented in Figure 4.5. 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.

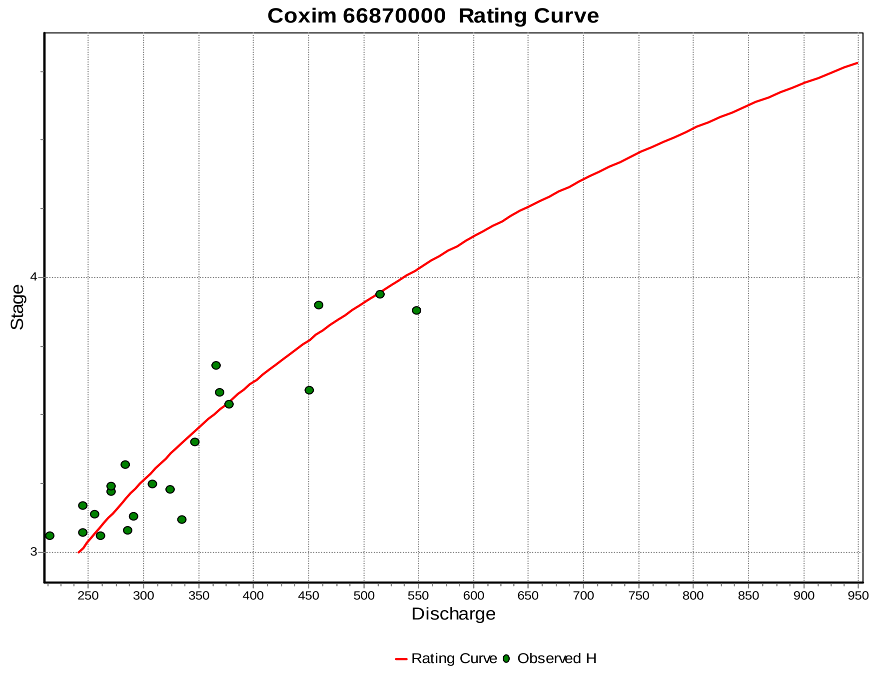


Figure 4.5: Coxim rating curve

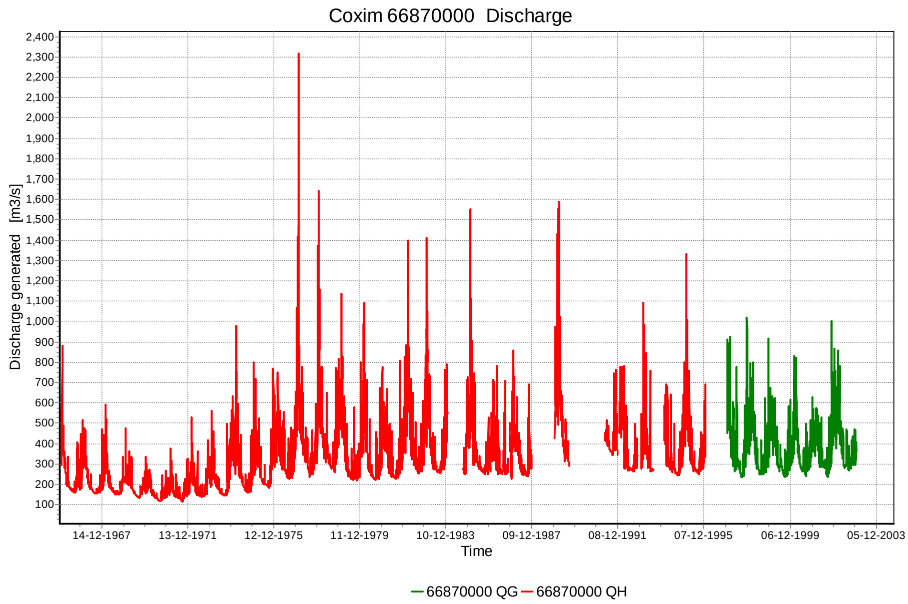


Figure 4.6 : Generated and ANA discharges at Coxim. Newly calculated discharges (1997 - 2003) are shown in green.

Discharges were calculated using the established rating curve. The discharge that is entered into the model is shown in Figure 4.6.

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

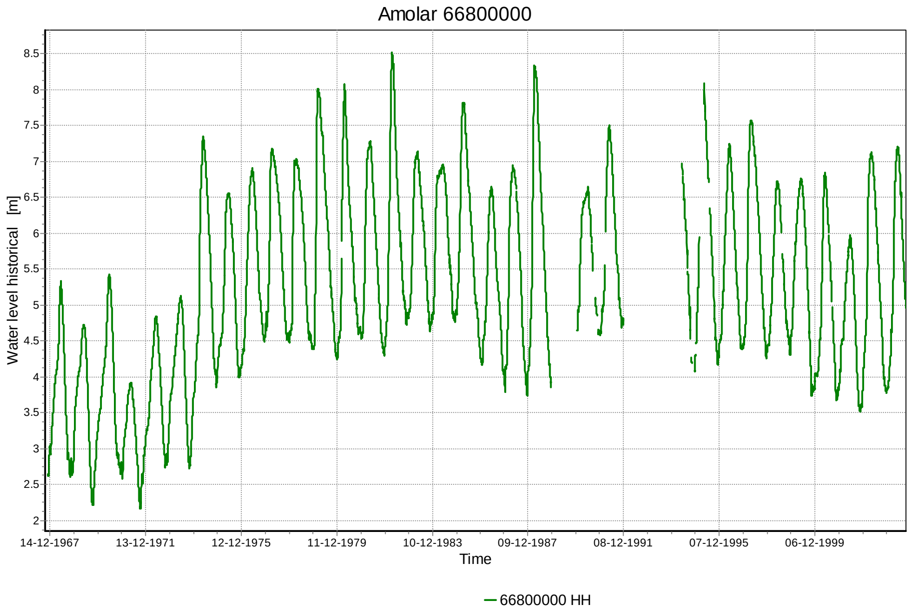


Figure 4.7: Water levels at Amolar

Figure 4.7 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.

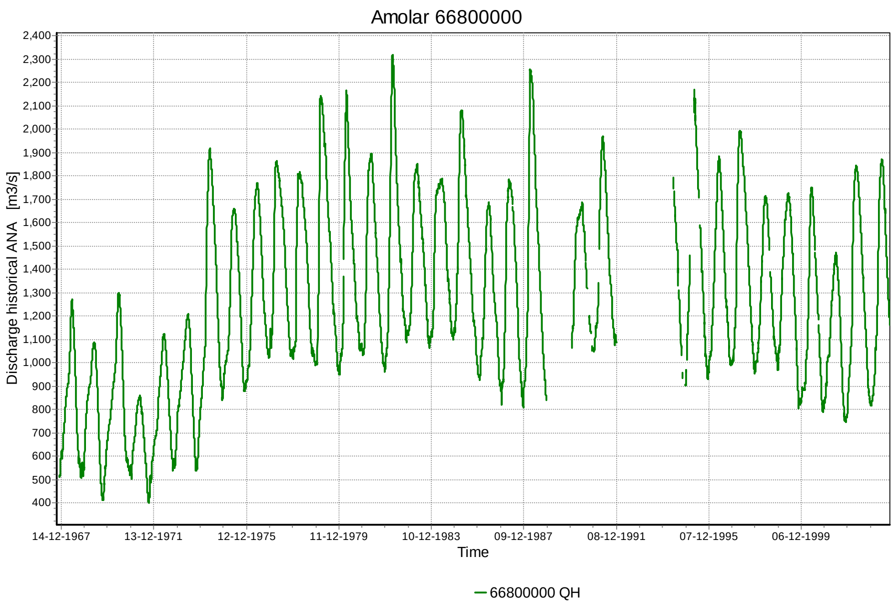


Figure 4.8: Discharge at Amolar

Figure 4.8 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.

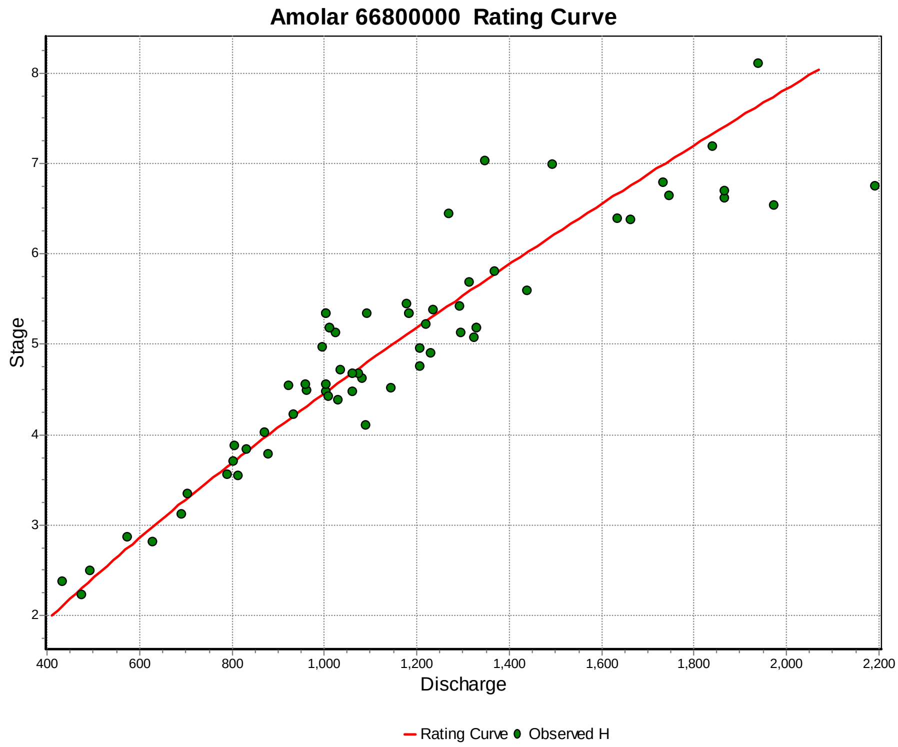


Figure 4.9: Calculated rating curve with discharge measurements used to derive the curve

Figure 4.9 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 Fransisco (66810000) is located approximately 60 km 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.

A first comparison of imported ANA discharges for São Fransisco with those of Amolar shows a considerable difference in the discharges at the two locations. Figure 4.10Figure 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 2.800 m3/s (2.200 m3/s at Amolar and 5.000 m3/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 4.11).

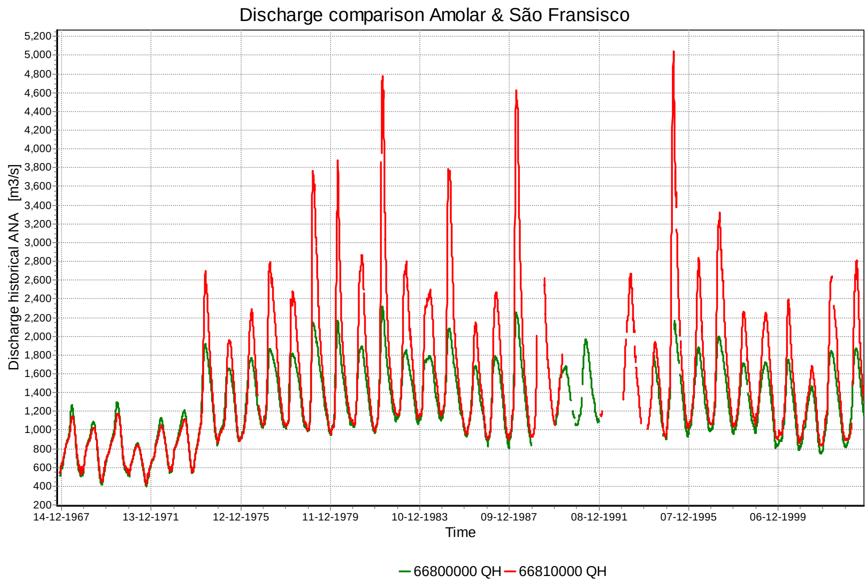


Figure 4.10: Comparison of discharge at Amolar & São Fransisco

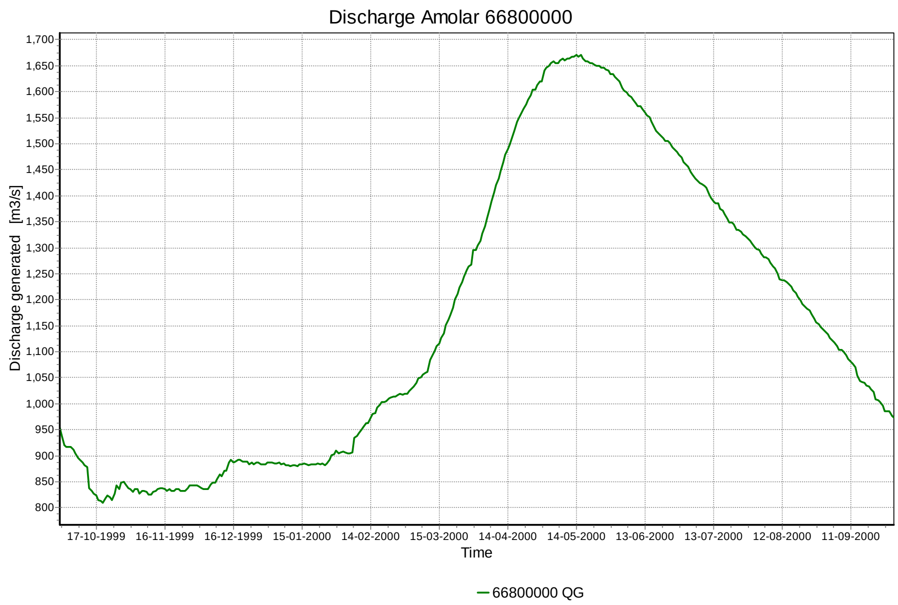


Figure 4.11: Discharge at Amolar for hydrological year 1999 - 2000

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

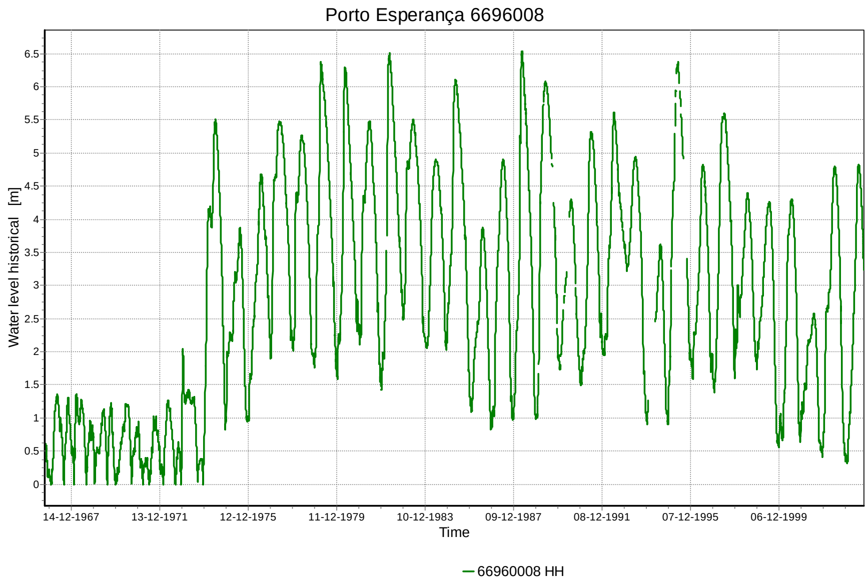


Figure 4.12: Water levels at Porto Esperança

Figure 4.12 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 the following series being used in the model:

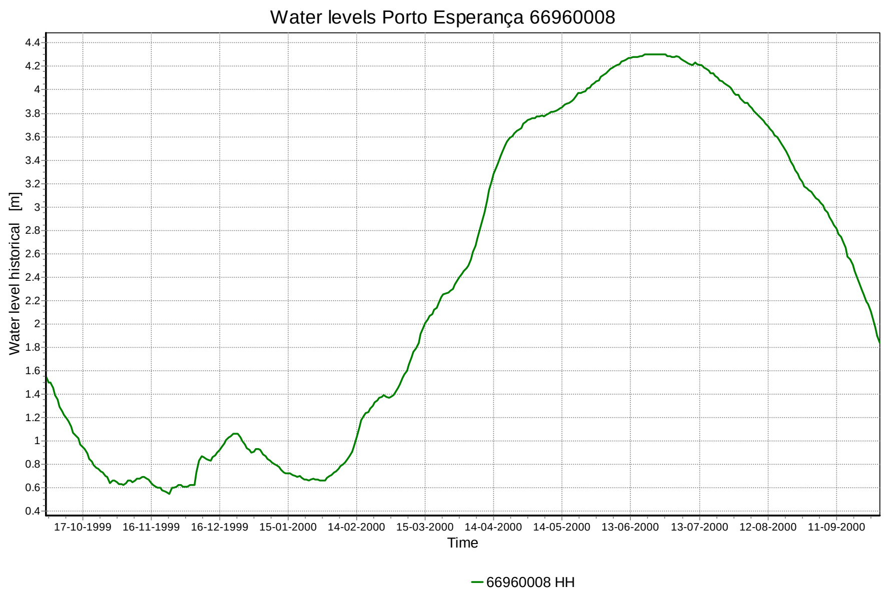


Figure 4.12: Water levels at Porto Esperança

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 4.13 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 01 October 1966 - 01 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 4.13 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.

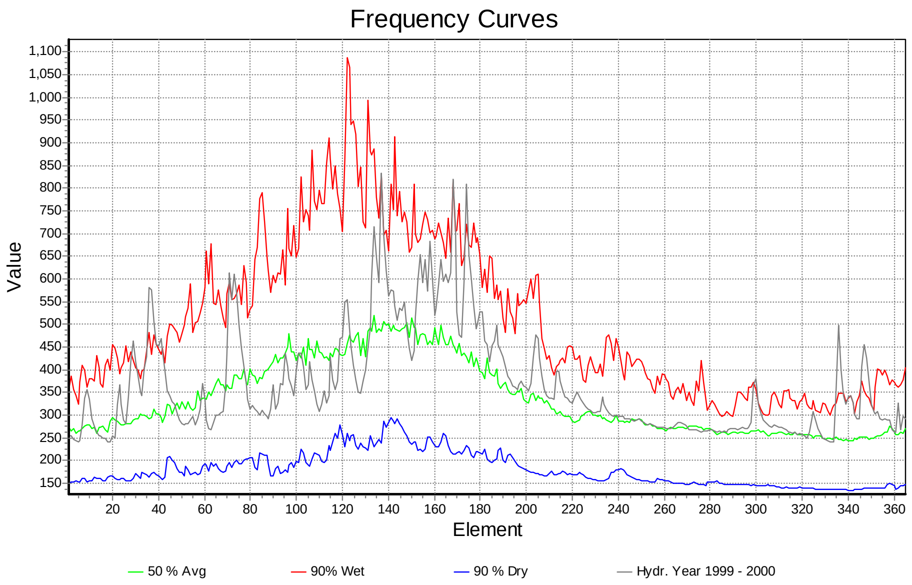


Figure 4.13: Hydrological year 1999-2000 and frequency curves for discharge at Coxim

In Figure 4.14 the frequency curves for discharge at Amolar are shown. The frequency curves are derived from the discharges generated 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.

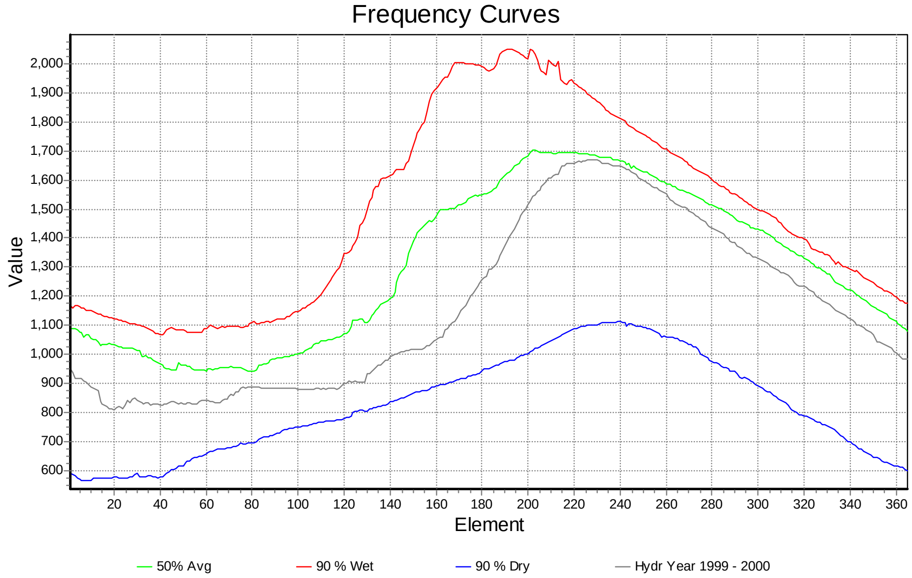


Figure 4.14: Frequency Curves for Discharge at Amolar

In Figure 4.15 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.

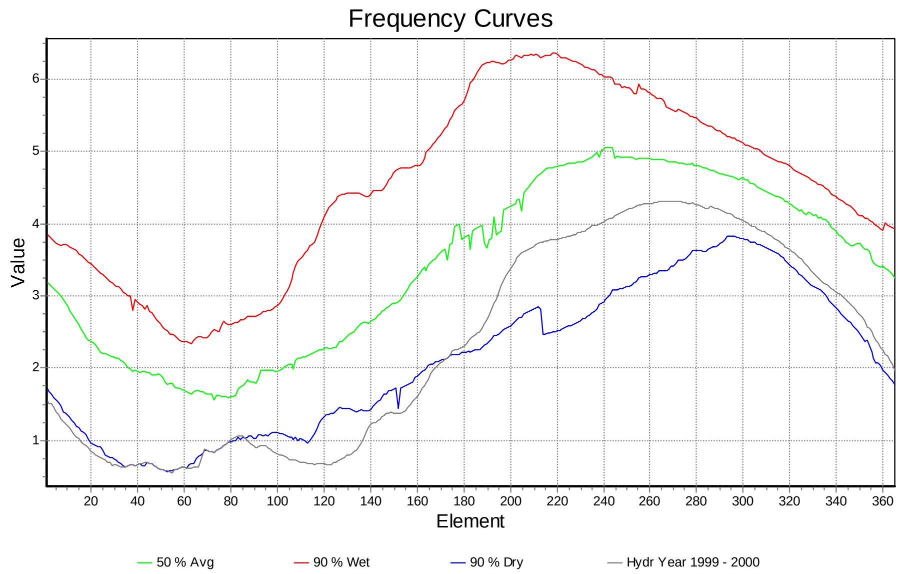


Figure 4.15: Frequency Curves for Water Levels at Porto Esperança

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 areal 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 4.16.

Figure 4.16: Data availability of 11 Precipitation data series

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 4.17.

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 4.18.

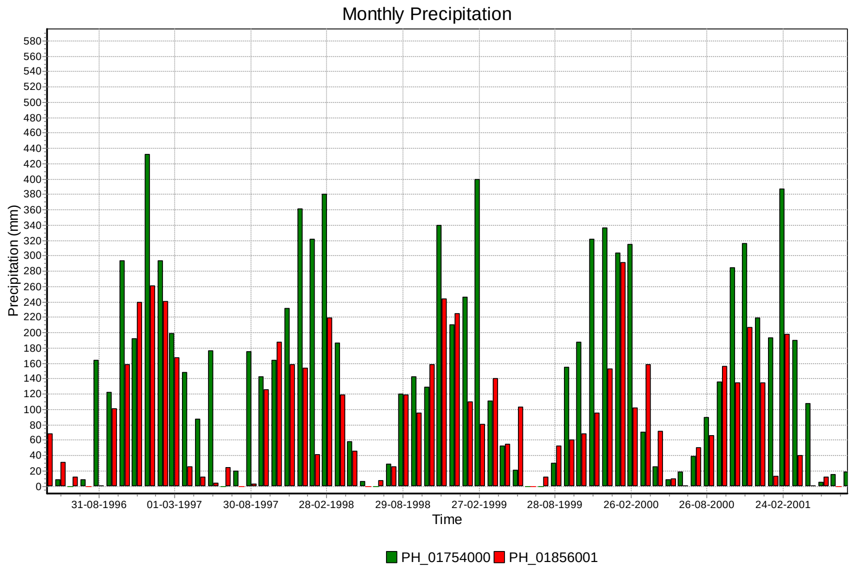


Figure 4.17: Monthly precipitation at Itiquira (Green) and Nhumirim (Red)

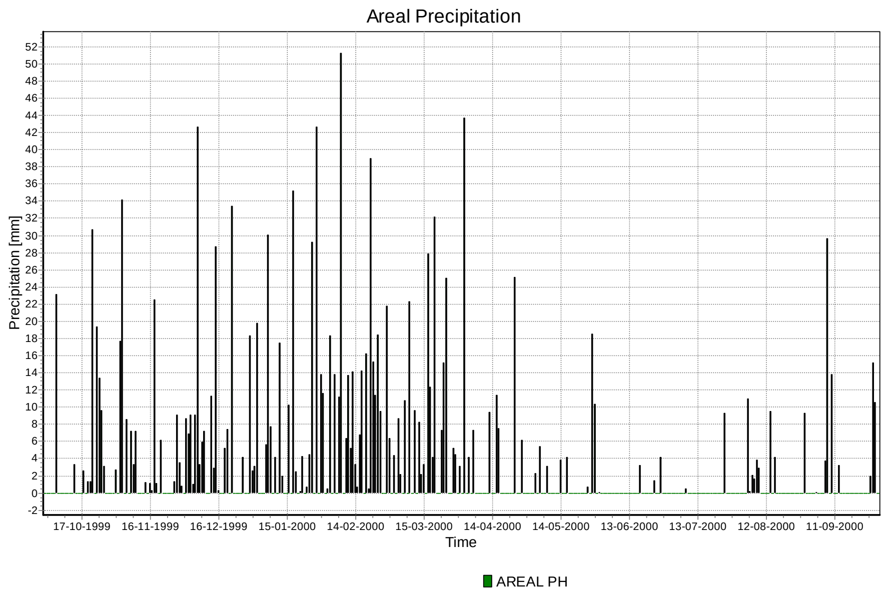


Figure 4.18: Areal Precipitation

Evaporation data

Evaporation data are available only at station Nhumirim. The complete series is shown in Figure 4.19.

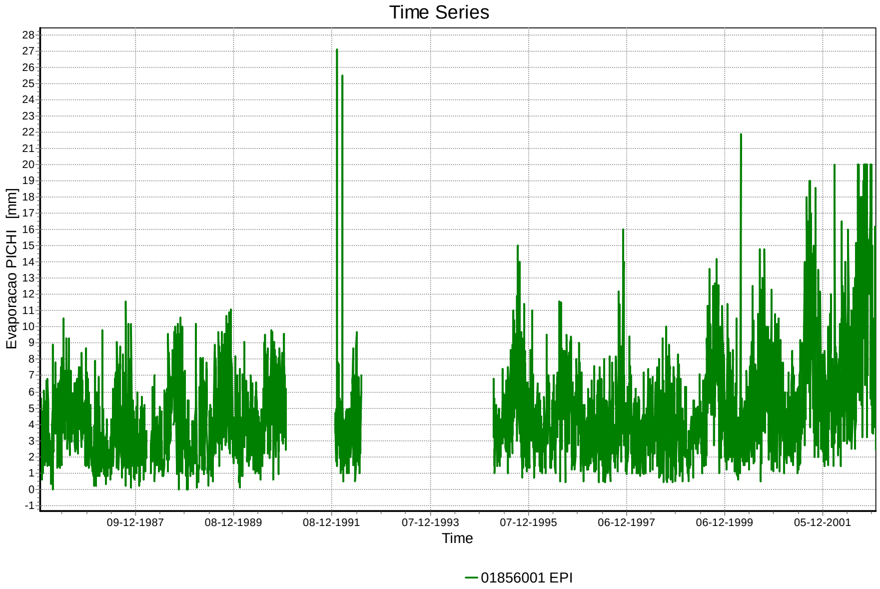


Figure 4.19: Daily evaporation at Nhumirim, Jan 1986 - Dec 2002

Figure 4.19 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 4.20

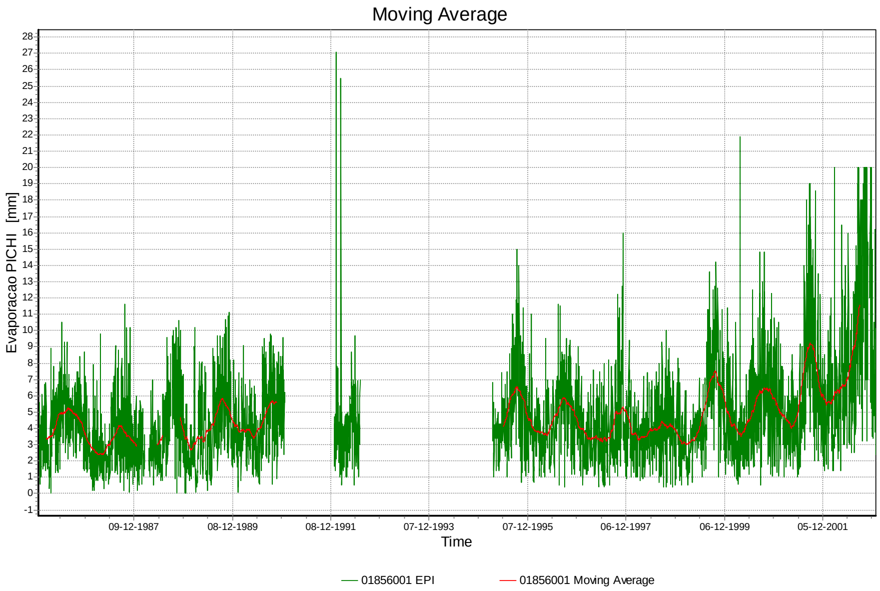


Figure 4.20: Daily evaporation including 60 day moving average

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 4.21).

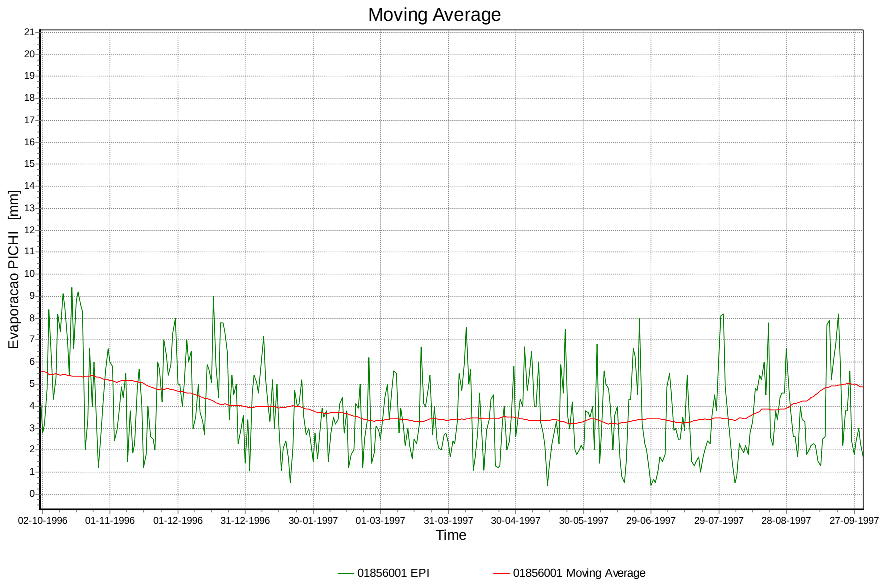


Figure 4.21: Evaporation for Oct 1996 - Oct 1997 including evaporation profile (60 day moving average)

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 procedure is very rough. The number of rainy days in each month remains the same, which is obviously a simplification of the actual situation.

In Figure 4.22 the frequency curves for monthly precipitation of the areal average are shown. The period of data used is from 01 January 1979 - 01 January 2002. The HYMOS series that was used is Areal PH.

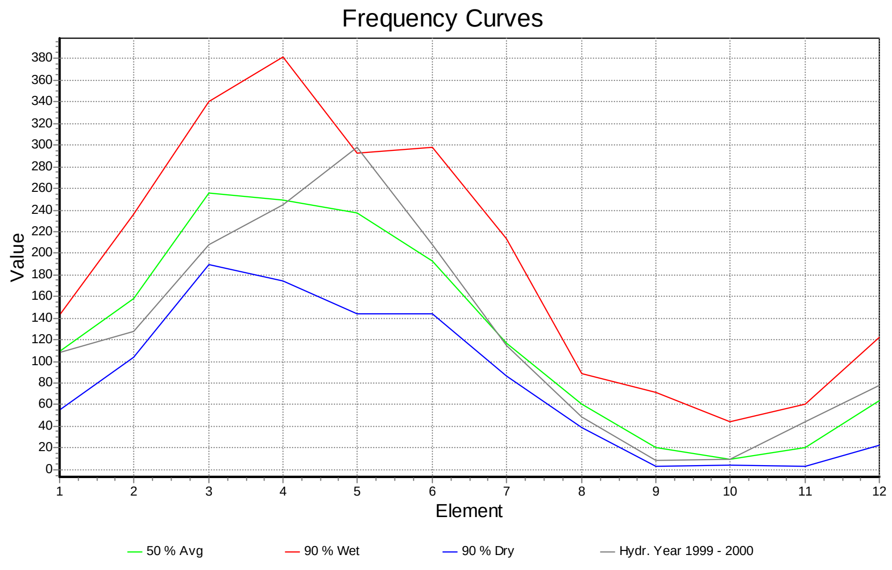


Figure 4.22: Frequency curves of monthly precipitation

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 chapter 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 Esperanca 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 Esperanca 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 in 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 * 900 m was used (based on a 90 * 90 m grid created by ITC)
- A grid with hydraulic roughness values was used (based on a vegetation map created 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 2000 mission (Chapter 3). The digital elevation model was corrected for drainage and vegetation. The resolution from the resulting elevation model was 90 * 90 metre. 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 * 900 metre was created. Figure 3.12 shows the digital elevation model with a resolution of 900 * 900 metre.

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 * 900 m was created (see Figure 4.22).

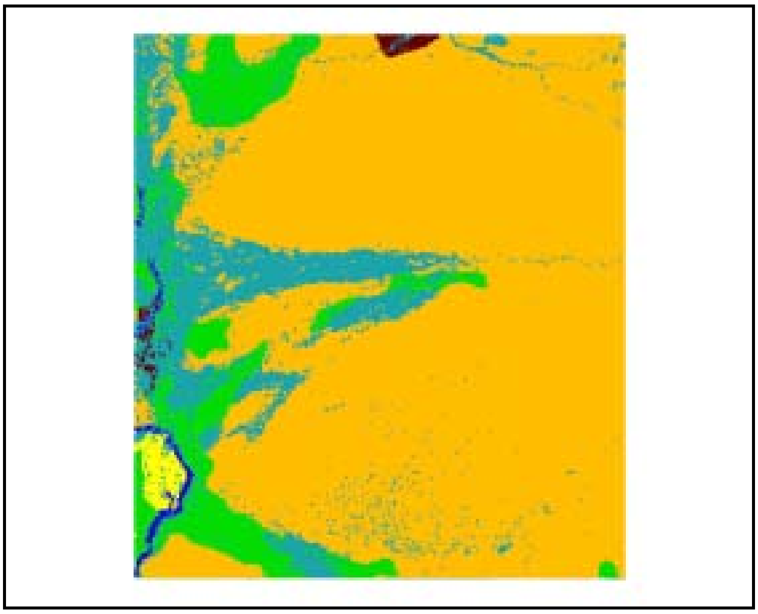


Figure 4.22 Grid with hydraulic roughness values; orange = 1m; dark blue = 0.003m; green = 1.5m; yellow = 0.4m; grey = 0.1m; dark brown = 5m and the value 4 is not on the map.

An improved vegetation map from Alterra was used in a later version of the model. This vegetation map had a resolution of 90*90 m. This improved vegetation map shows more spatial variation than the first vegetation map (see Figure 4.23). 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	galery forest	7.0	zachthoutstruweel
2	(semi) decidual forest	7.0	zachthoutstruweel
3	form. pioneiras (transicao)	5.0	zachthoutstruweel
4	savana forested (cerradao)	6.0	doornstruweel
5	savana arboreal (cerrado)	3.0	droge ruigte + 10%
6	savana gramineo lenhosa	4.0	riet
7	savana gramineo lenhosa + arboreal	3.5	average of 5 and 6
8	pionier vegetation	1.5	homogene natte ruigte
9	area cultivada	0.8	verruigd grasland
10	baia	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.

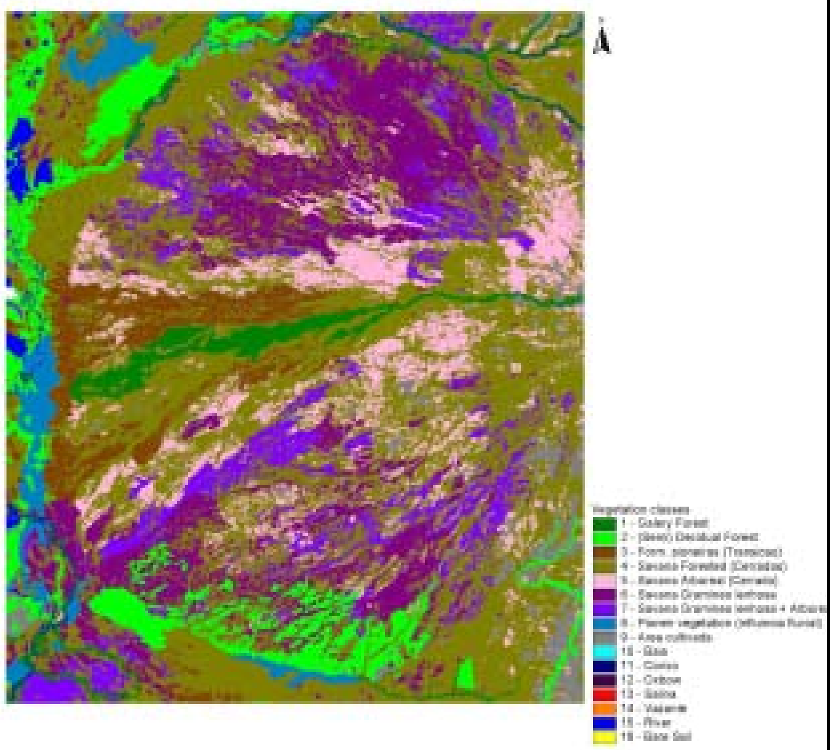


Figure 4.23 Improved vegetation map from Alterra

Thereafter the grid was aggregated to a grid with a resolution of 900*900 m 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 4.24.

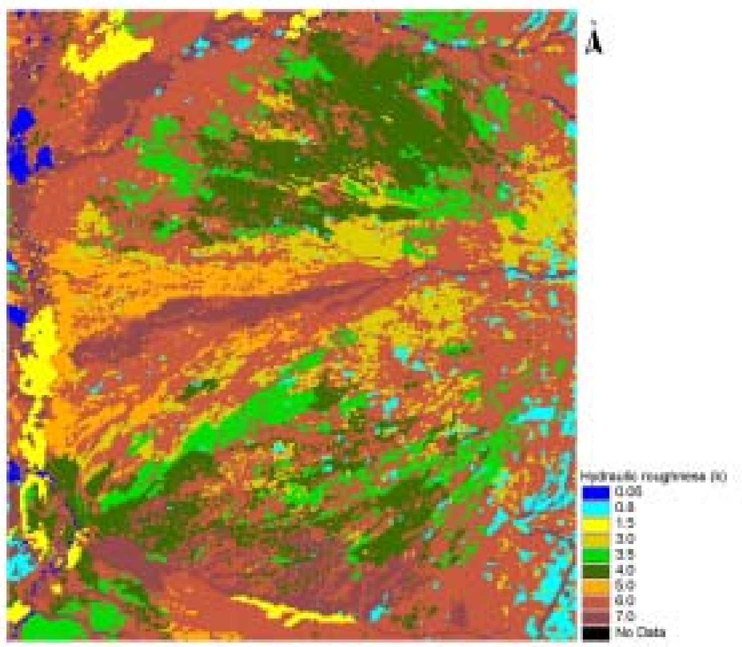


Figure 4.24 Map with hydraulic roughness values derived from improved vegetation map

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 4.25). 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 4.25 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*900 m 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.

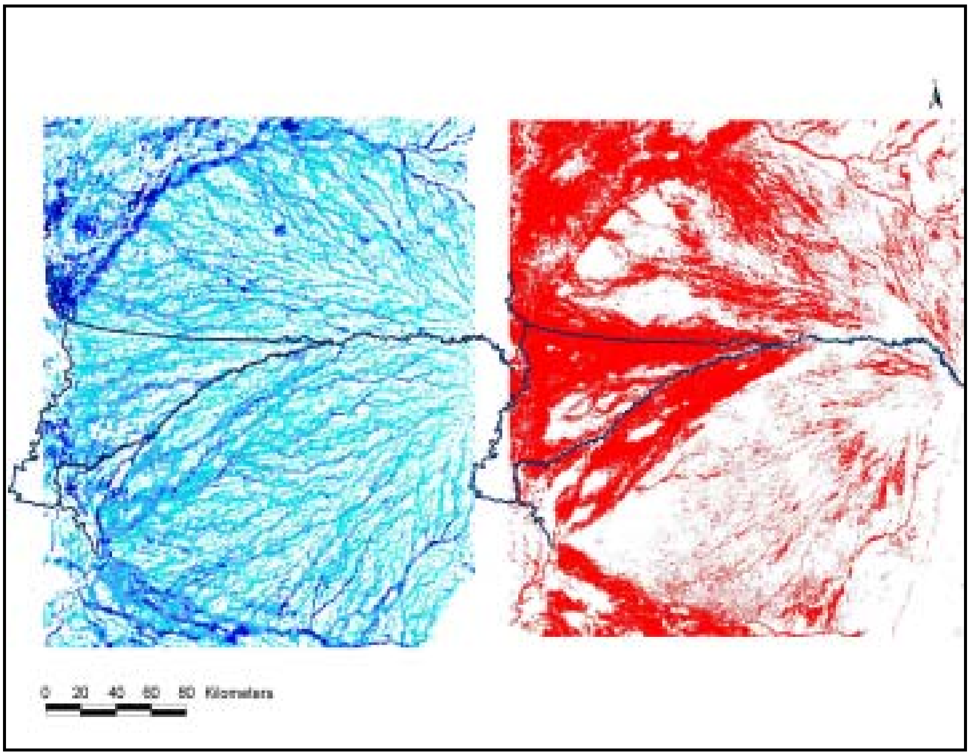
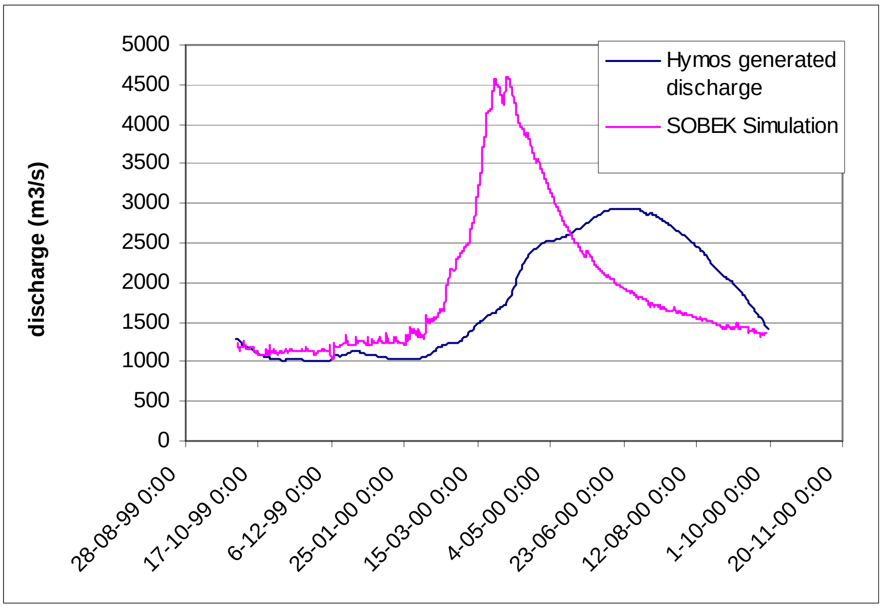


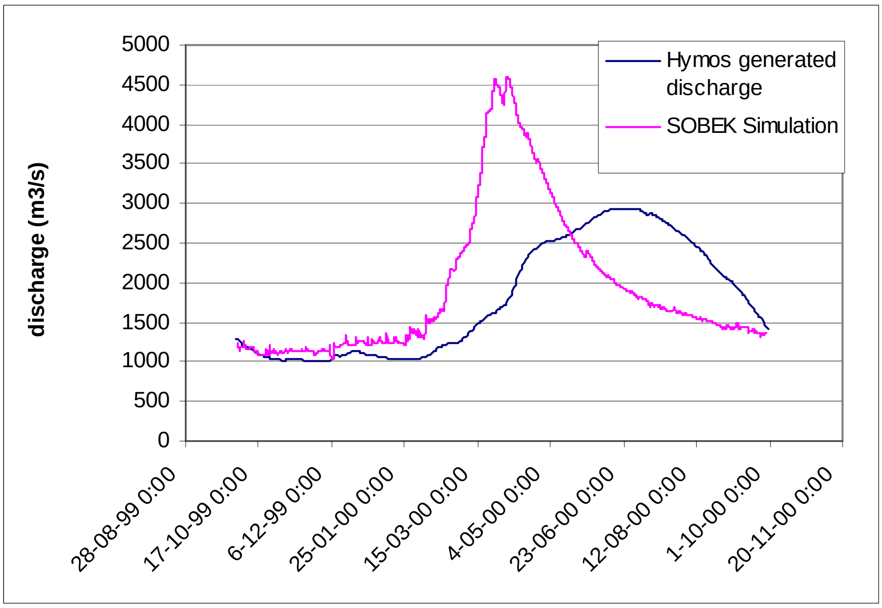
Figure 4.25 Comparison of simulated inundated areas from the calibration run (left) with satellite data from April 2003 (right)

The observed discharges at Porto Esperanca 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.

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.



A



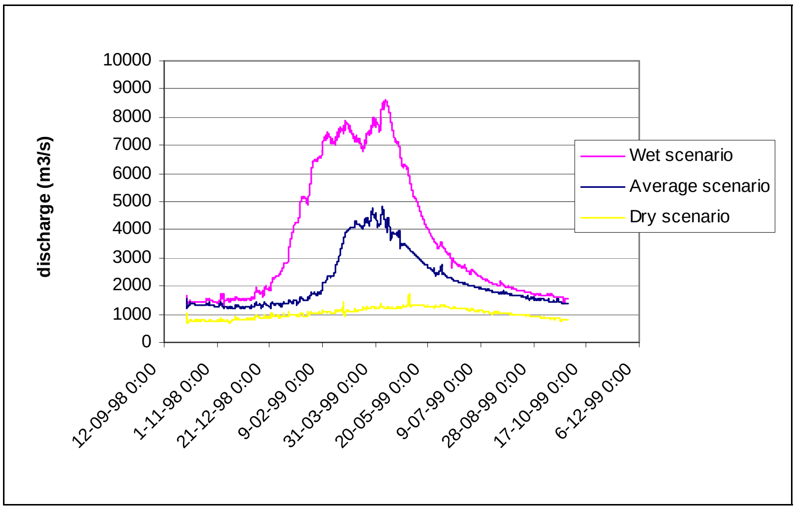
B A

Figure 4.26A shows the simulated discharge with SOBEK and the generated discharge with Hymos at PortoEsperança Figure 4.27B 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 4.27. 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.



FigurFigure 4.27. Simulated discharges for the three scenarios just upstream of Porto Esperanca.

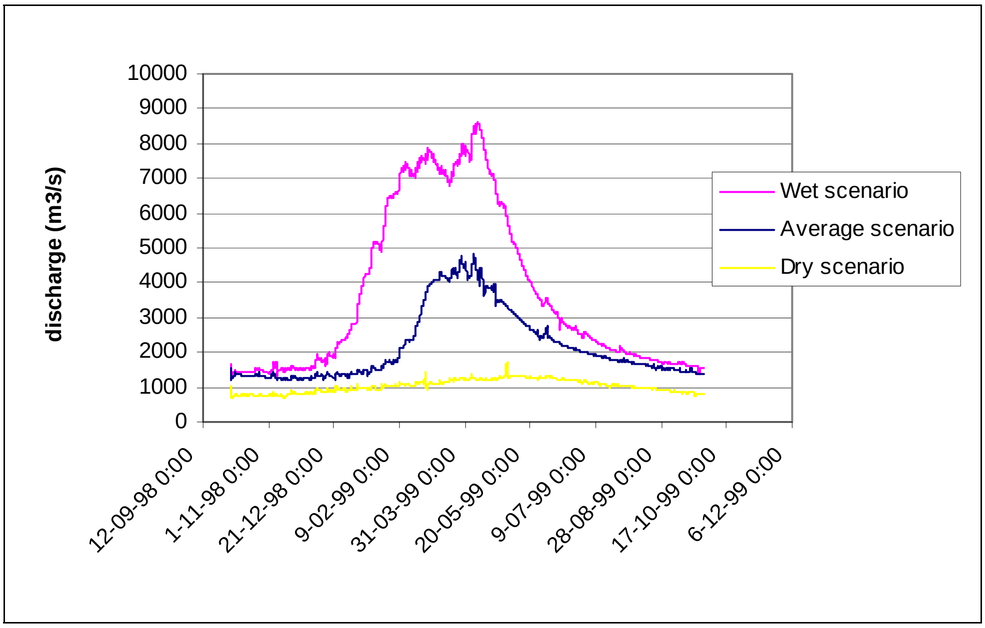


Figure 4.27 Discharge at Porto Esperanca for the three different scenarios

Maps of the inundated areas for the 27th of March (during the wet-season) in all the three scenarios are presented in Figure 4.28, Figure 4.29 and Figure 4.30.

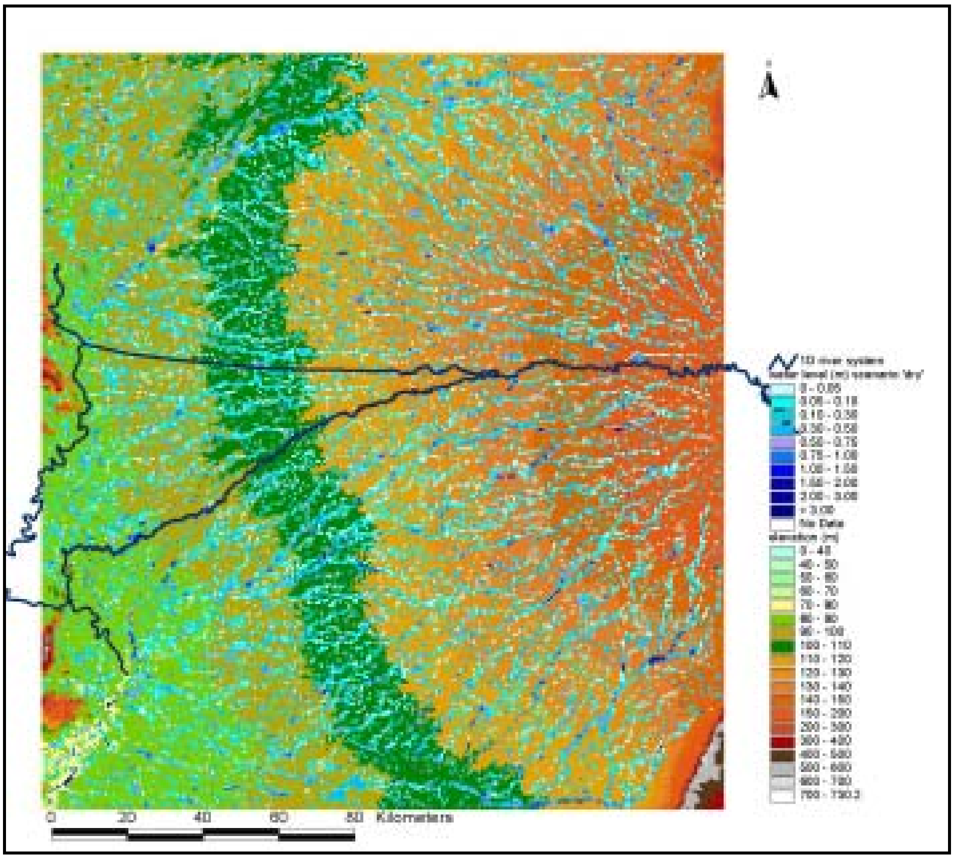


Figure 4.28 Simulated inundation areas for the 'dry' scenario

Figure 4.28 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.

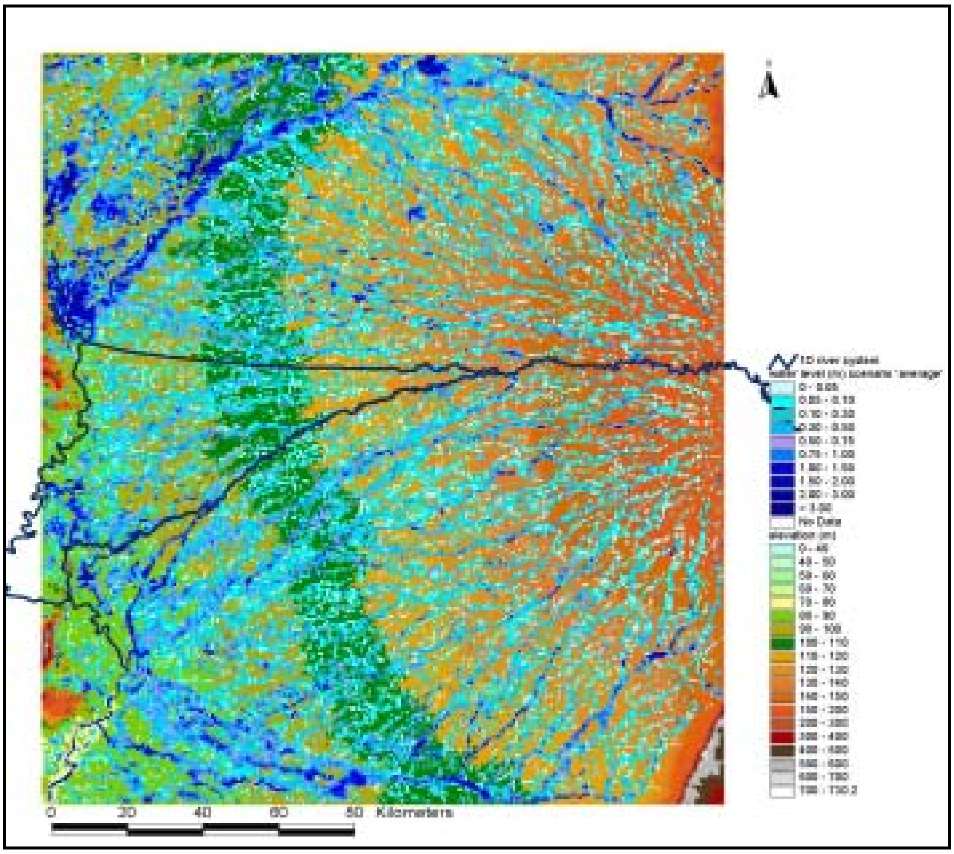


Figure 4.29 Simulated inundation areas for the 'average' scenario

Figure 4.30 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.

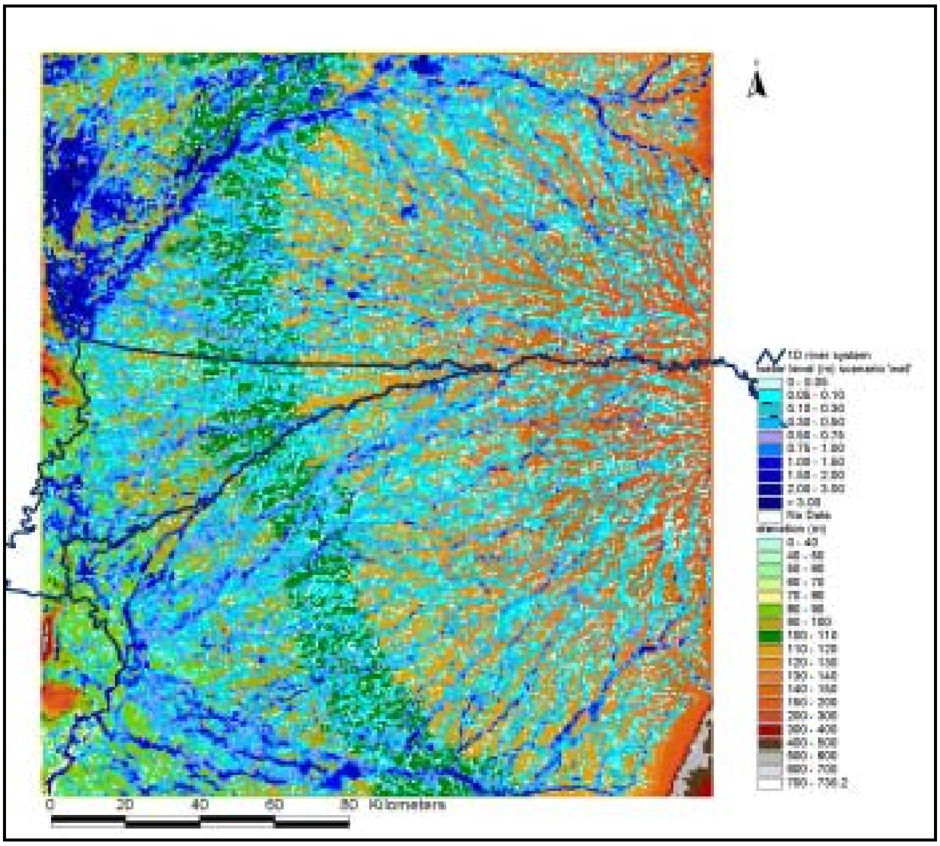


Figure 4.30 Simulated inundation areas for the 'wet' scenario

In Figure 4.30 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.

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

5.1 Introduction

This report 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 Río Taquarí in the Pantanal.

Measurements of the following river aspects between Coxim and Corumba 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 Corumba;
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.

The report has been written by mr. C. Stolker. Arc-View assistance was provided by mr. G. Groenveld (Alterra) and mr. M. Ververs (WL | Delft Hydraulics).

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

The field-trip 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.

Water depth and water level

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 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).

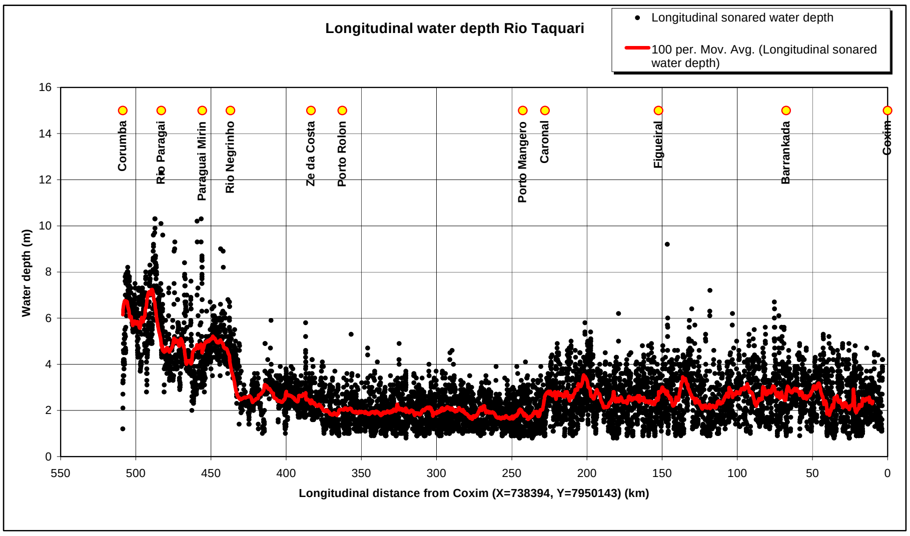


Figure 5.1 Longitudinal profile of the water depth along the thalweg in the Rio Taquari (March 30th to April 4th)

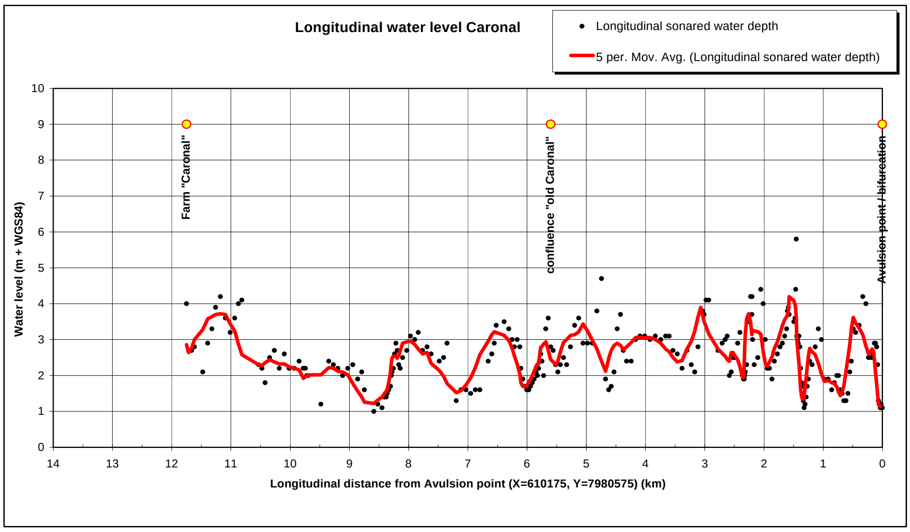


Figure 5.2 Longitudinal profile of the water depth along the thalweg in the New Caronal (March 30th to April 4th)

Although, the presented longitude (X) and latitude (Y) geographical position of a common GPS is quite accurate, the delivered altitude (Z) is very unreliable (> 10 m). 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 Corumba showed 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.

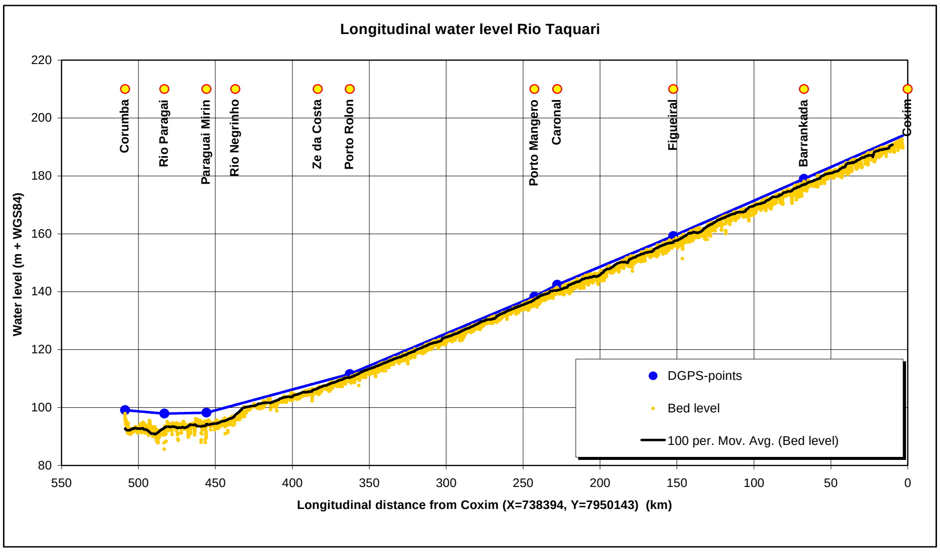


Figure 5.3 Longitudinal profile of the water level and the bed level along the thalweg in the Rio Taquari (March 30th to April 4th).

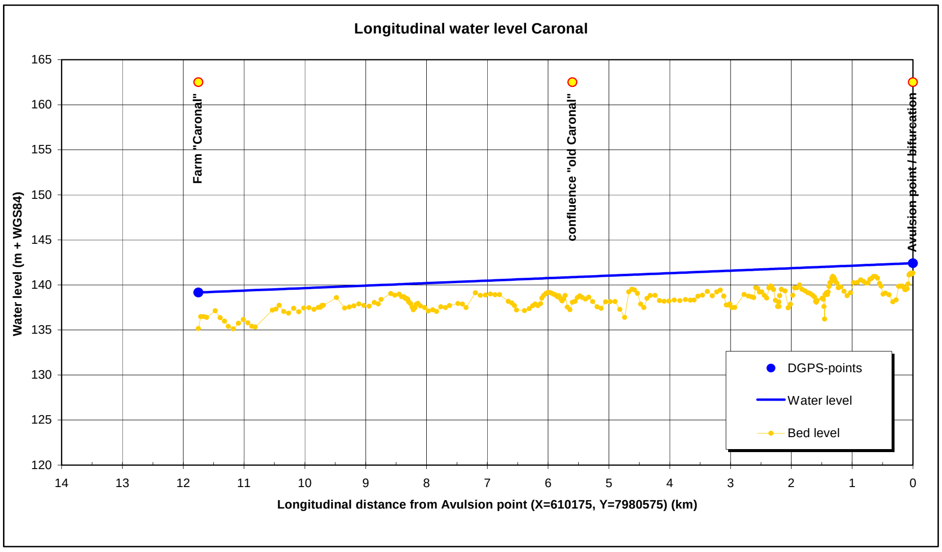


Figure 5.4 Longitudinal profile of the water level and the bed level along the thalweg in the New Caronal (March 30th to April 4th)

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 10 m.
- 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 Ze 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.

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 – Paragai Mirin	363 – 456	0.144
	Paraguai Mirin – Rio Paraguai	456 – 483	0.011
Caronal	bifurcation – Farm :"Caronal"	0 – 12	0.277
Rio Paragai	Corumba – Rio Taquari	456 – 483	0.017

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

5.2 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 5.2. 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 5.1 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:

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

Table 5.1 also provides the geographical location (X and Y) of the samples obtained.

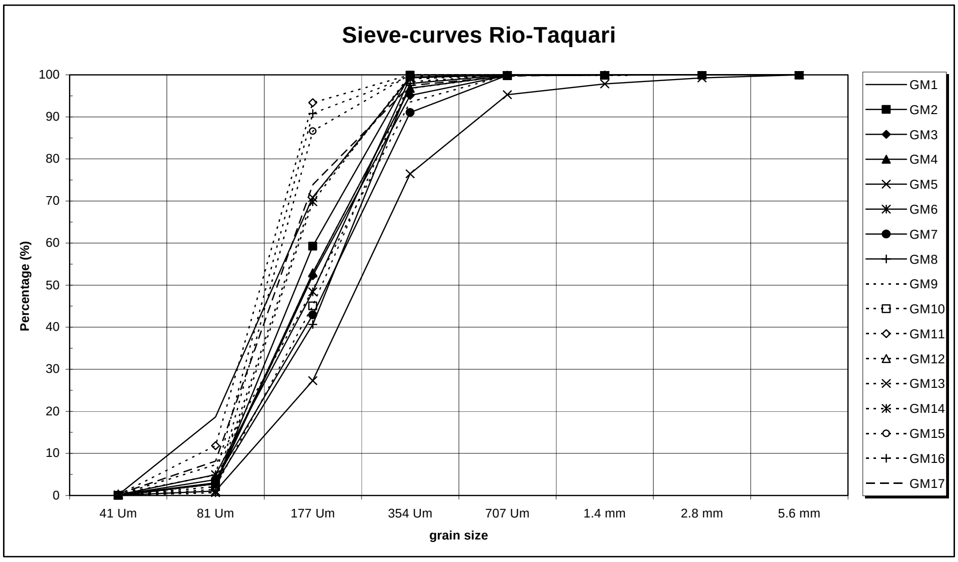


Figure 5.2 Accumulated sieve curves of the river bed samples

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	Zeda 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	Paragai Mirin	463.2	0.120	0.142	0.226	0.298

Table 5.1 Characteristic grain sizes (in mm)

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 5.3, 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.

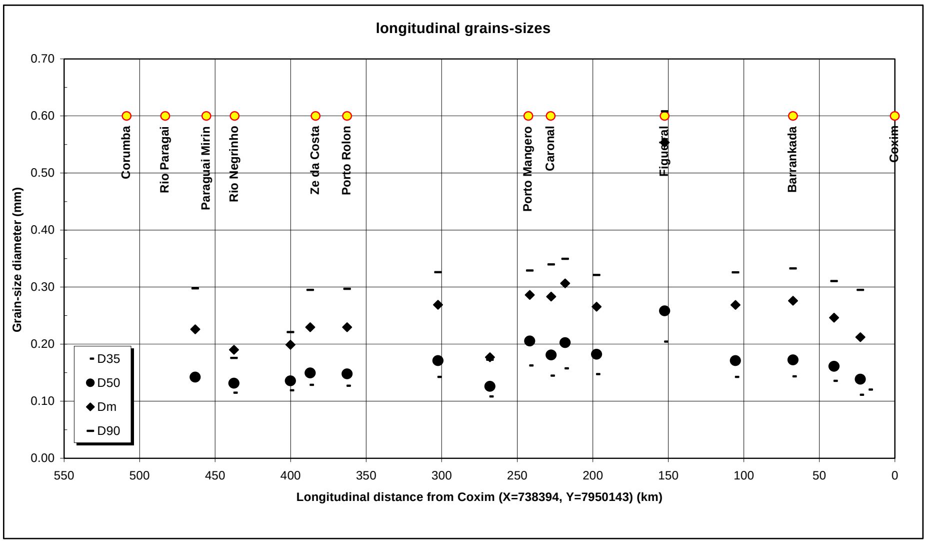


Figure 5.3 Longitudinal distribution of the grain sizes

5.3 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 traveling 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_o is the level of zero velocity or discharge, which, in case of a hydraulically smooth surface can be determined by the following equation:

$$z_0 \quad \frac{\iota}{117} \qquad (5.3)$$

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

$$\iota \mid 11,6\frac{\tau}{u_*} \mid 1.6\frac{C}{\mathrm{Re}\sqrt{g}}h \qquad (5.4)$$

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:

$$u(z) \mid \frac{u_*}{\rho}\ln\left(\frac{z}{z_0}\right) \qquad (5.5)$$

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 $u(z) \mid U_{wl} \mid u(h)$ 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 (FigureFigure 5.4 and along the upper part of the New Caronal (Figure 5.5). 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.

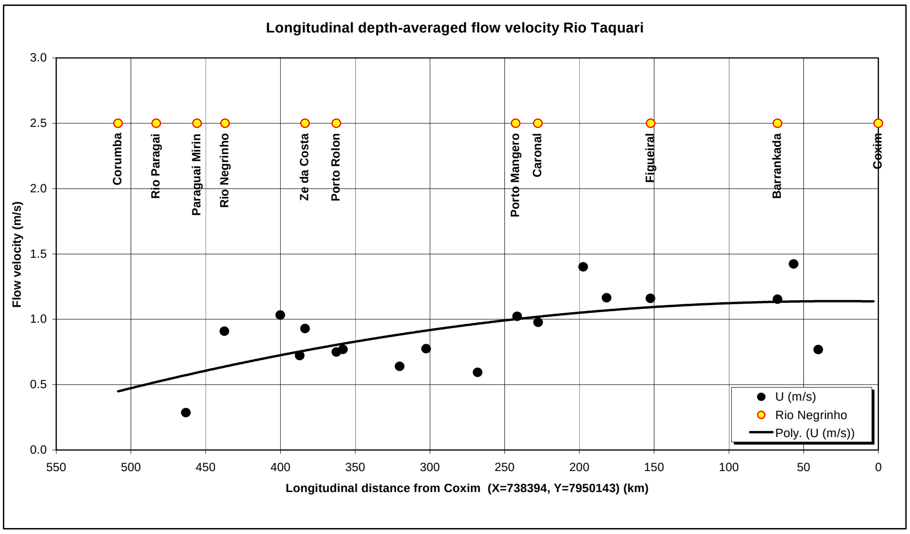


Figure 5.4 Longitudinal distribution of the depth-averaged flow velocity along the thalweg in the Rio Taquari (March 30th to April 4th)

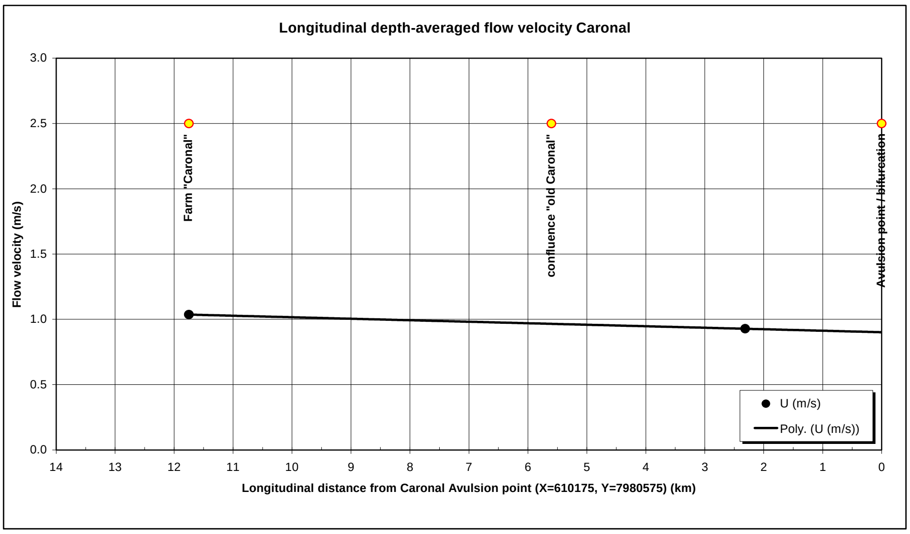


Figure 5.5 Longitudinal distribution of the depth-averaged flow velocity along the thalweg in the New Caronal (March 30th to April 4th)

5.4 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.

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
Pto. Rio Negrinho	466581.67160	7917487.92688	80,35	Jan 1997	yes
P. Mirim Faz. S. Bened.	453918.54138	7912946.51475	101,2	Jan 1997	yes
Figueiral	665741.26991	7983813.42499	154,2	Jan 1997	yes

Table 5.2 Previously measured cross-sections

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 5.2.

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 5.3 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.

Name	**Figure**	**Vertical change**		**Transversal change**			
	App.dix. A	**Sediment-ation (m)**	**Erosion (m)**	**Shifted Left > 10 m**	**Shifted Right > 10 m**	**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. Mirim	A-21	unknown[1]	unknown[1]	no	no	no	no

Table 5.3 Indication of morphological changes at cross-section locations

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.

5.5 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 an 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 Río Taquarí.

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 Río Taquarí. 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 Río Taquarí 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 Río Paraguai have become higher
Hypothesis 4	The distance to the Río 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** (see Appendix A), 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 σm and 70 σm). 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 accomodated 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 are 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 = 200 m^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 5.6).

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.

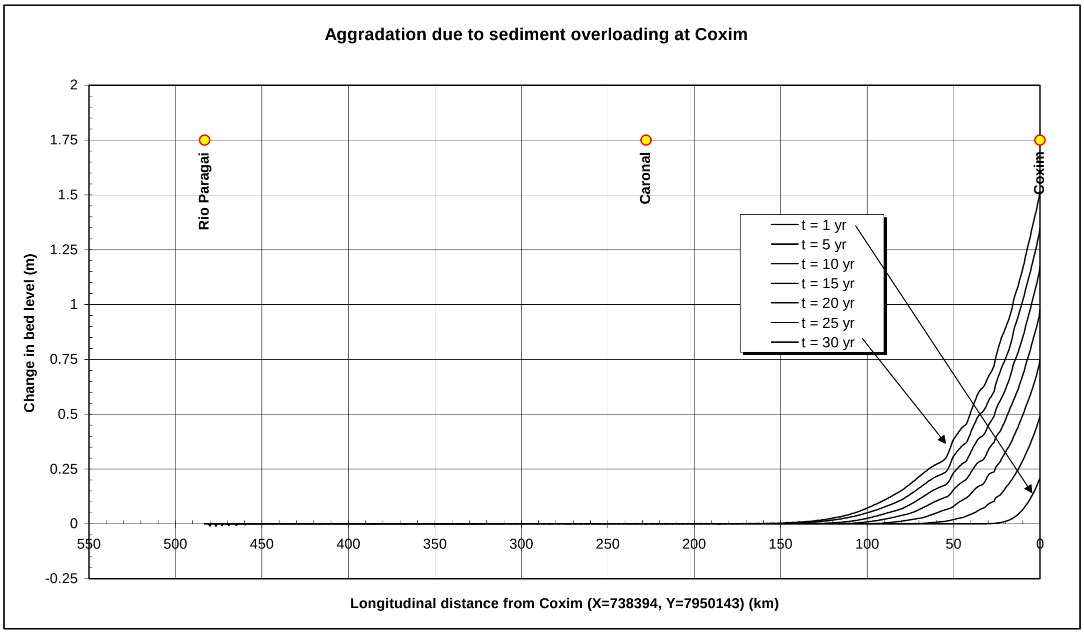


Figure 5.6 Aggradation due to sediment overloading at Coxim

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 1.5 m, up to more than 2 m at peak discharges (corresponding changes in discharge on basis of QH-curves: more than 100 m^3/s for the lower water situations up to 600 – 1.400 m^3/s at peak discharges). Also in the Rio Paraguai, at Amolar, the water levels would have risen between 1.25 and 3 m (corresponding changes in discharge between 100 and 1,000 m^3/s). At Porto Esperança in the Rio Paraguai the water levels would have risen between 1 and 6 m.
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 Río Paraguai are becoming higher, they push up the water levels on the Río Taquarí and its surrounding terrains (‘backwater effect’). This underlies the third hypothesis: **the water levels on the Río Paraguai have become higher**.

The previous chapter 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 1 m up to 6 m 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 5.7). 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.

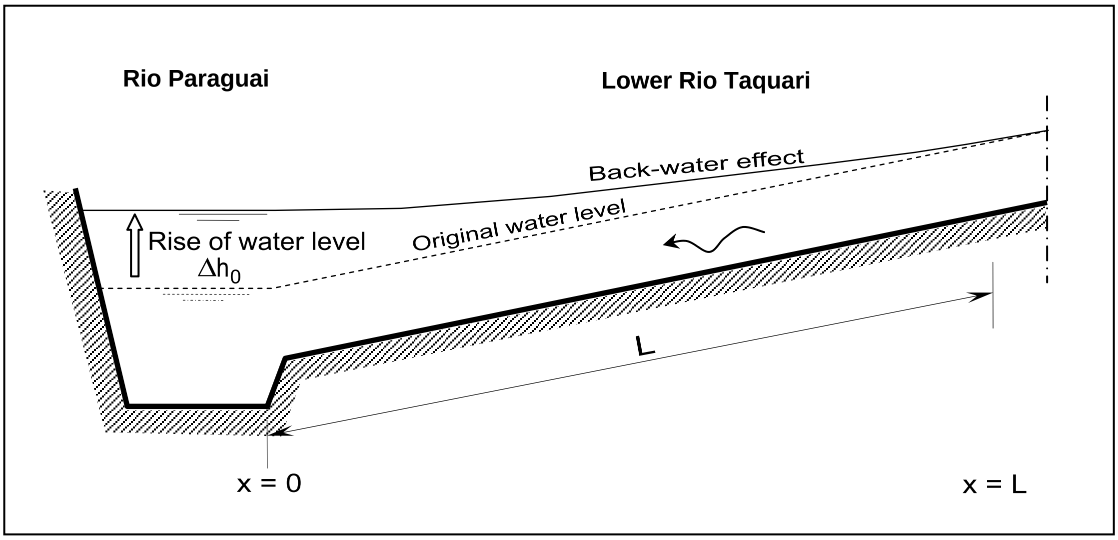


Figure 5.7 Example of the back-water-effect

A rise of the water level at location X = 0 km 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:

$$\frac{dh}{dx} = i_b \left(\frac{h^3 - h_n^3}{h^3 - h_c^3} \right) \qquad (5.6)$$

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	=	200 m^3/s
River width B	=	50 m
Chézy-roughness C	=	50 – 70 m$^{1/2}$/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:

$$k_s = 2.5 \cdot D_{90} = 2.5 \cdot 2 \cdot D_{50} \tag{5.12}$$

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 – 70 $m^{1/2}/s$.

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 5.8. This figure shows the bed level profile used and the calculated water levels up to a distance of 140 km 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 5.9.

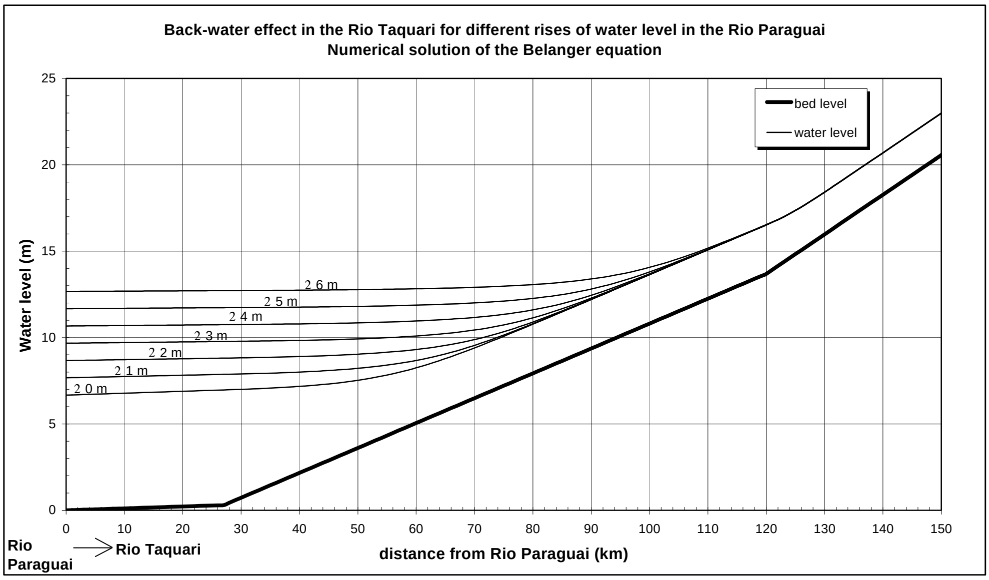


Figure 5.8 Backwater effect in the lower Taquari based on the transition in longitudinal bed slope

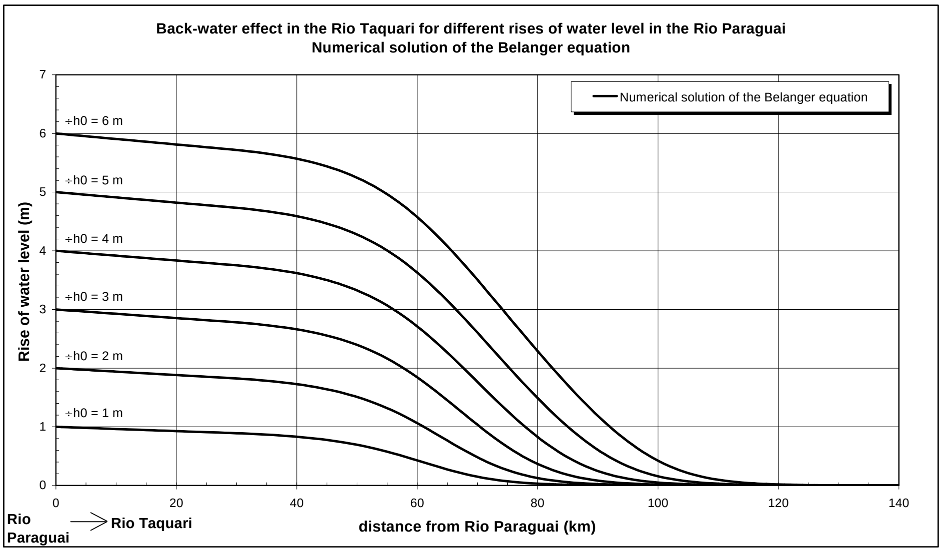


Figure 5.9 The actual rise of water level in the lower Taquari due to water level rises in the Rio Paraguai

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 80 km the downstream water level rise of 1 m will hardly be noticed anymore (downstream of Zeda Costa). For a downstream water level rise of 6 m, this location lies further upstream at a distance of approximately 110 km (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 Río Paraguai has become longer**. Channel migration of the Río Paraguai or the downstream reach of the Río Taquarí 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 Río Taquarí and its surrounding terrains.

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

$$Q = CBh^{3/2}i^{1/2} \qquad (5.15)$$

The slope *i* is defined by:

$$i = \frac{\Delta z}{L} \qquad (5.16)$$

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:

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

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 5.9, 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 5.9 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.

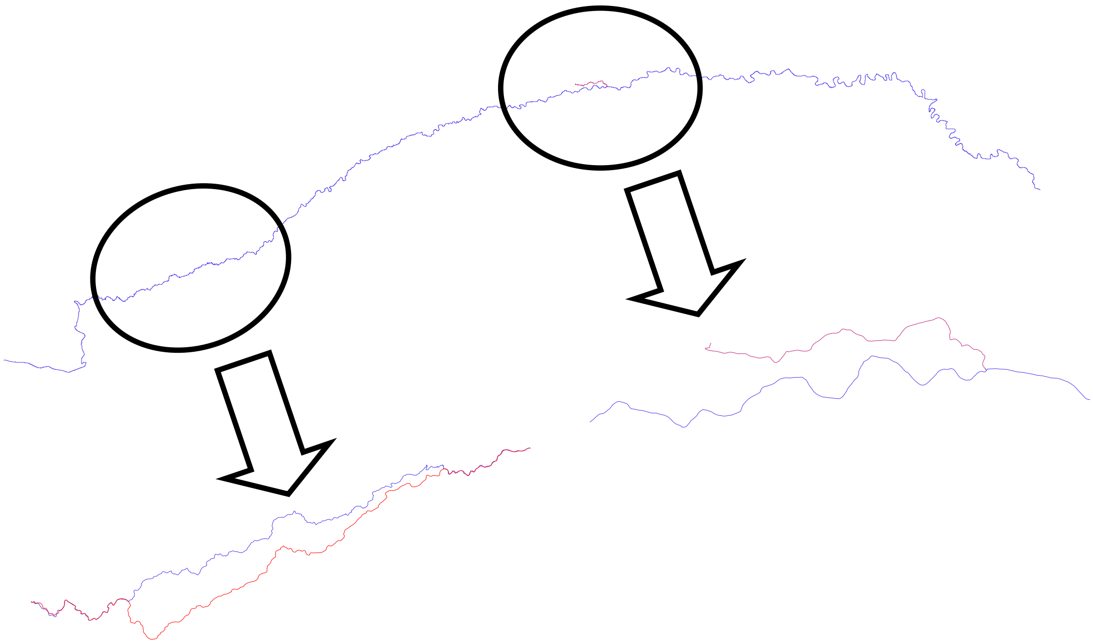


Figure 5.9 Sailed path along the Rio Taquari during the last field trip

Possibly the abandonment of the Taquarí Velho in favour of the Río Negrinho - Paraguai Mirim at the Arrombado Zé da Costa has led to larger distances to the Rio Paraguai (the Río Negrinho and the Paraguai Mirim became active in 1988). In 1996, they already conveyed 70% of the discharge of the Río Taquarí (information Sergio Gaudino 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 Río Taquarí. Recent satellite images suggest that the course of the Río Taquarí 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 Río Taquarí and the Río 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. The large-scale one-dimensional adaptation of the river bed is explained schematically in Figure B-1 (see Appendix B).

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 20 m 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 Chapter 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 Zeda Costa and the Paraguai Mirin.

5.6 Conclusions and recommendations

Flooding and sedimentation along the Lower Taquarí 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 5.4.

Hypothesis	Findings	Plausibility

Hypothesis	Findings	Plausibility
1. 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 150 km of the Lower Taquari (downstream Coxim).	NO
2. 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
3. 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 60 km upstream along the Taquari by 0.4 m. ∉ A 6 m higher water level on the Paraguai increases the water level 80 km 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
4. Longer distance to Paraguai	∉ No signs of change in sinuosity. ∉ No signs of eastward or westward movement of the Rio Paraguai.	NO
5. 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)
6. Widening and increased braiding	∉ Cross-sections recorded during the field mission show that, within the last 10 years, the river widened by about 20 m between Zeda 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

Table 5.4 Summary of the findings regarding the causes of the sedimentation and flooding problems along the Taquari

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 conservationalists. 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 LEDESS PANTANAL

6.1 Background of Decision Support Systems and the LEDESS model

The environment surrounding us is subject to a continuous evolution in development plans. This may be planning at the expense of nature or in favour of nature development. Planners wonder what are the consequences of their scenarios for nature 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 targets. This is the so-called cyclic planning. 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).

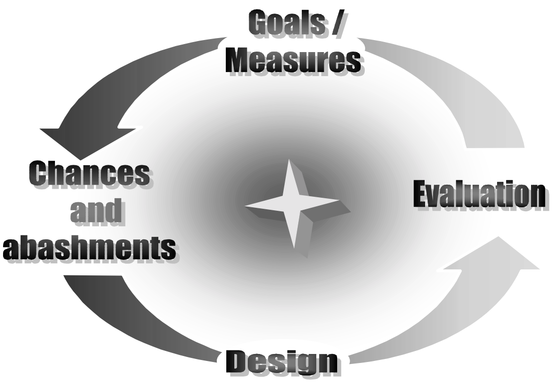


Figure 6.1 Cyclic planning procedure: the base for a DSS

In the past several different models (COR, Gelderse Poort-model, SCN; Harms et al., 1991, 1994, 1995) have been developed to simulate and evaluate nature. In 1996 the former DLO-Staring Centre (now: DLO-Alterra) developed LEDESS (Landscape Ecological Decision & Evaluation Support System) which was used in several projects[1].

LEDESS is an example of a GIS based expert system. It is a computer model used to assess and evaluate the effects of land use changes on nature. LEDESS works by confronting GIS maps of the existing landscapes with proposed measures and ecological know-how. The results are GIS maps and tables of the expected vegetation and fauna distribution patterns.

[1]
- *'Natuur-modellenkoppeling voor nationale milieu-en natuurverkenningen, co-financed by the Rijksinstituut voor Volksgezondheid en Milieuhygiene (RIVM);*
- *Sub-projects of the future explorations 'Verstedelijking & Infrastructuur', 'Landbouw' en 'Ecologische Hoofdstructuur van Natuurverkenningen 1997' (Farjon et al, 1997; Ypma et al, 1997; Bal & Reijen, 1997).*
  The Natuurverkenningen 1997 are performed by IKC-Natuurbeheer, RIVM, DLO-Institute for Forest- and Nature Research and DLO-Staring Centre in assignment of the Ministry of Agriculture, Nature Management and Fisheries.

6.2 Modelling Concept: Ecotopes of the Pantanal-Taquari

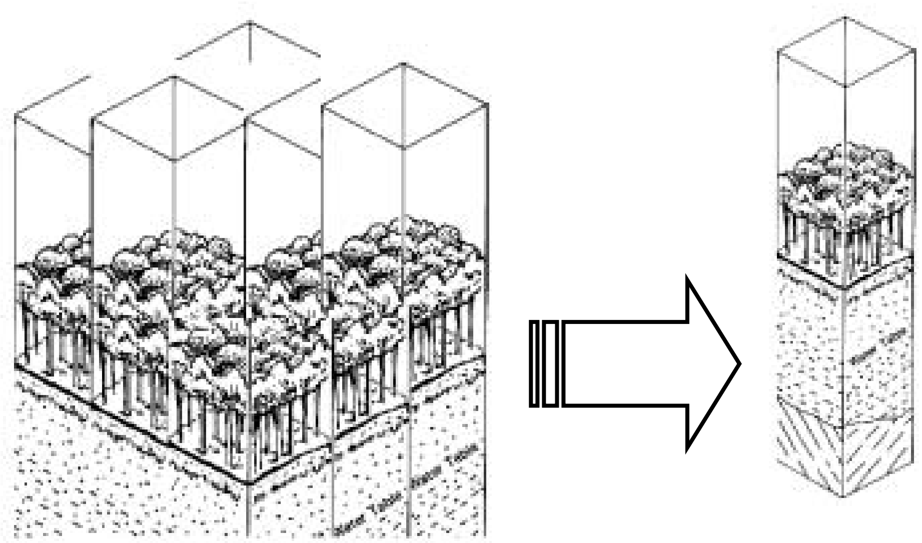
River management and flooding prevention in the landscape and river system are mostly focused on introduction of measures. Examples classic engineering:

- Digging, dredging
- Changing the path of the river
- Building dykes

To minimize unexpected effects, scenario studies can be used to analyse different solutions and their probable impacts.

LEDESS evaluates scenarios to see if they are possible from an ecological viewpoint and determines their consequences for nature and/or their economic effects. This way, choices can be made on what kind of nature or land use type is desired and the fauna suitability of the location as well as the economic profitability. The landscape-ecological modelling in LEDESS is based on a simplified view of ecosystems. Four components are considered, namely landscape, physiotope, vegetation and fauna, furthermore their interactions are taken into account. The relations are topological (vertical) and chorological (horizontal). Processes are present as a derivation from the different ecosystems, in other words they are not explicitly present.

The concept of the ecotope originates from landscape ecology. An ecotope is here defined as 'a physically limited ecological unit, whose composition and development are determined by abiotic, biotic and anthropogenic aspects together'. Ecotopes are more or less homogeneous units on the scale of the landscape, identifiable by their similarities and differences in geomorphologic and hydrological characteristics, vegetative structure and land use.



Landscape consisting of several homogeneous units ***ecotope: homogeneous unit***

Figure 6.2 The Landscape consists of ecotopes

The concept of the physiotope is used, in relation to the ecotope, for the unit that is homogeneous in respect of the abiotic conditions that are important to biotic aspects. In other words, if management and stage of development are the same, then the physiotope and ecotope are the same physical unit.

The typology for the Pantanal-ecotopes are intended for use in studies in dynamic water systems, therefore the classification of ecotopes is based on conditional factors of these systems. These factors are related to natural processes that may be controlled by means of landscaping and management. The ecotopes are classified on the basis of three general factors affecting abiotics, vegetation and fauna:

- **Morphodynamics**: mechanical forces exercised by water and sediment (erosion, transport and deposit of sediment, flow of water and surge); in this case new geomorphology-data had to be developed
- **Hydrodynamics**: physiological and chemical effects of water (duration, depth and time of flooding, as well as the type of the water); In this case 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
- **Land use / vegetation dynamics**: effects of human intervention i.e. conscious landscaping and management (from (natural) grazing or rough pasture management to intensive agricultural use); but also the developing of pioneer vegetation to forest or savannah. 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

A more detailed description of the modelling of these three factors (the used data sources and model knowledge) can be found in the next paragraphs. To obtain more information about the quality of the ecotopes themselves, for example, more details are required about the species and their relation with vegetation. As a result, smaller eco-elements can be distinguished within the ecotopes, but such data is most of the time not available for the total area.

6.3 Schematisation of the Model

Creating the System attributes

The Ledess-Pantanal project consists of one system. The system describes the geographical space (in this case the dynamic ecotope system spatial located on the alluvial fan of the Pantanal-Taquari river). The system contains all abstract system attributes concerning the Pantanal-Taquari (e.g. vegetation, physiotopes). Within the Ledess-Pantanal model the system attributes can be categorized. System attributes can belong to several categories. All the (abstract) system attributes are combined with sources to create a real model.
The main model input (vegetation structure, physiotope, measures/targets) in reality are not classified. They show a continuous range of characteristics. However, to be able to use them in LEDESS they need to be classified. The material present, and what you want to investigate defines what these categories look like. Figure 6.3 describes the main categories that are present in an Ledess-Pantanal project:

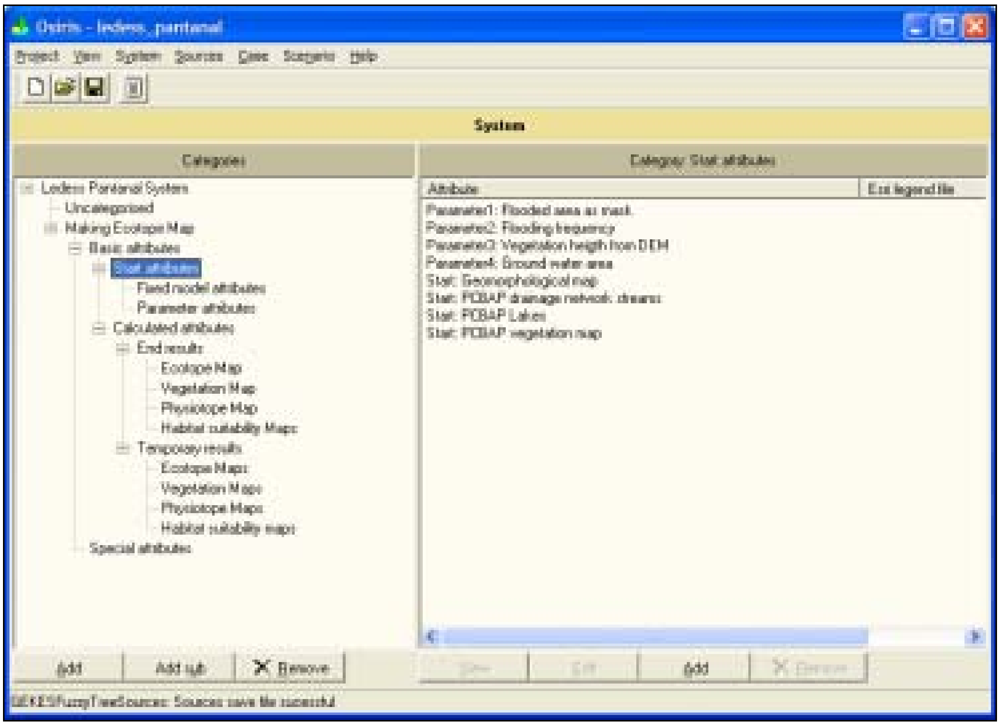


Figure 6.3 attributes for calculation of the Dynamic ecotope map and the Habitat suitability maps

1. Basic attributes
   - Fixed model attributes:
   - Parameter attributes
2. Calculated attributes
   - Ecotopes Map
   - Vegetation Map
   - Habitat Suitability maps
   - All the temporary calculation results (calculation steps)

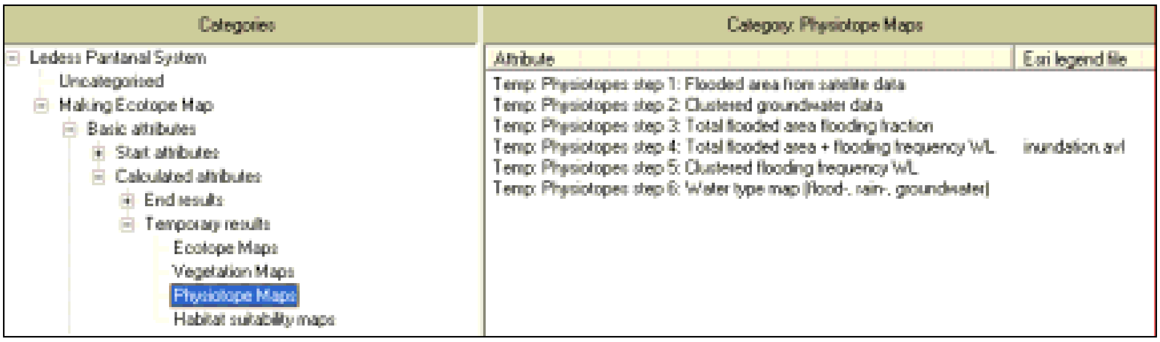


Figure 6.4 example temporary attributes for calculation of the End Physiotope map

Definition of sources: data and knowledge

The sources in the Ledess-Pantanal model consist of knowledge and data that quantify and/or qualify a system. A source can consist of a knowledge matrix, an Esri Avenue script, an Esri grid, or a decision tree. For instance, a source can be an Esri grid with land use, or a knowledge matrix that translates land use to landscape structure elements including legend colours varying between red and green;

Ledess-Pantanal supports four types of sources at this moment of edition (December 2003), namely: Esri grids; Esri Avenue scripts; Knowledge matrices; Decision trees. 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 (as described in §0). Every knowledge matrix is visualized in a table. Because visualization in more than two dimensions is impossible in a table the other dimensions can be fixed. In that case the higher dimensions are considered to be constant. Every knowledge matrix has a unique name.

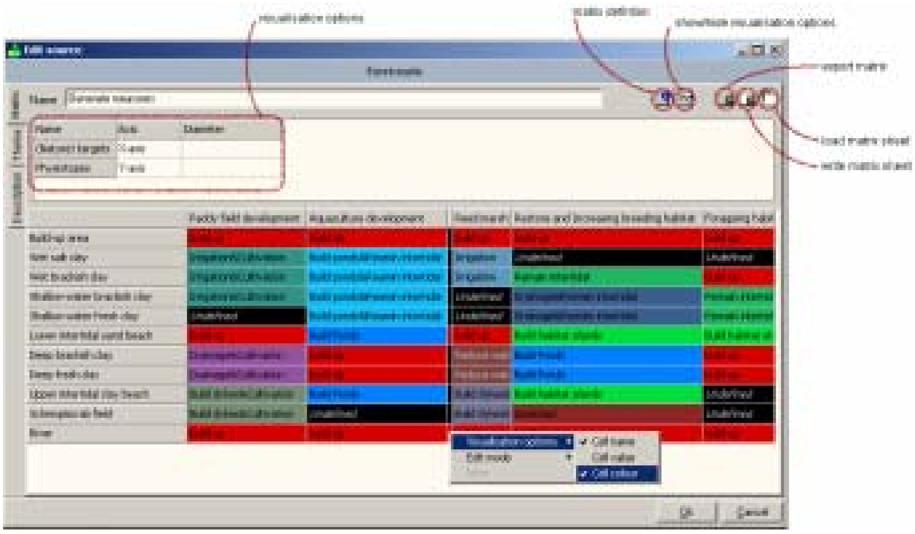


Figure 6.5 – Knowledge matrix source

A knowledge matrix is defined on the basis of a system attributes. Every dimension agrees with a attributes. In one knowledge matrix each dimension has to be defined in combination with a different theme. The result range of a knowledge matrix is also based on a system attribute and can correspond with a system attribute in one of the dimensions.

Overview of LEDESS-Pantanal sources

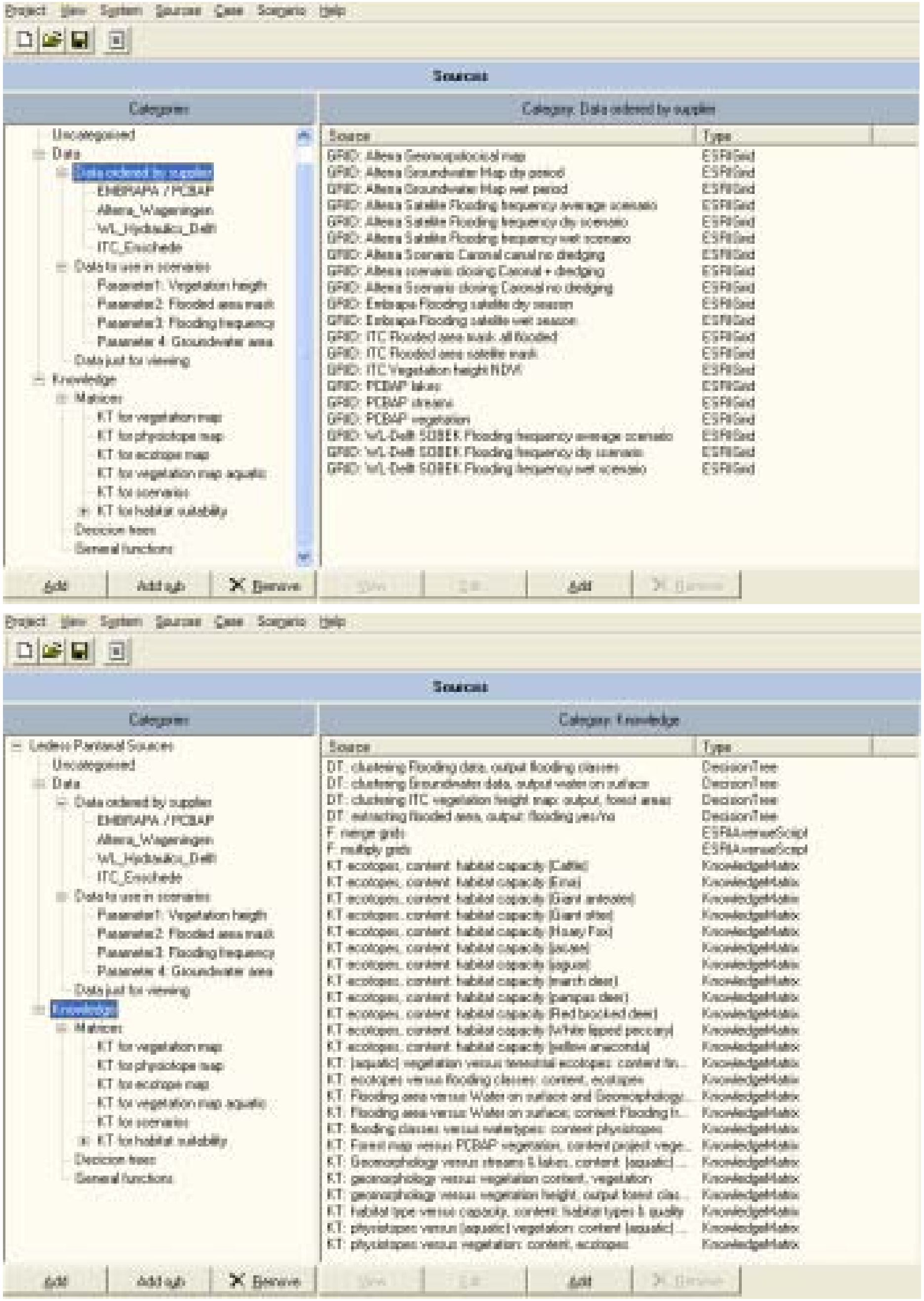


Figure 6.6 – Sources: Data and Knowledge

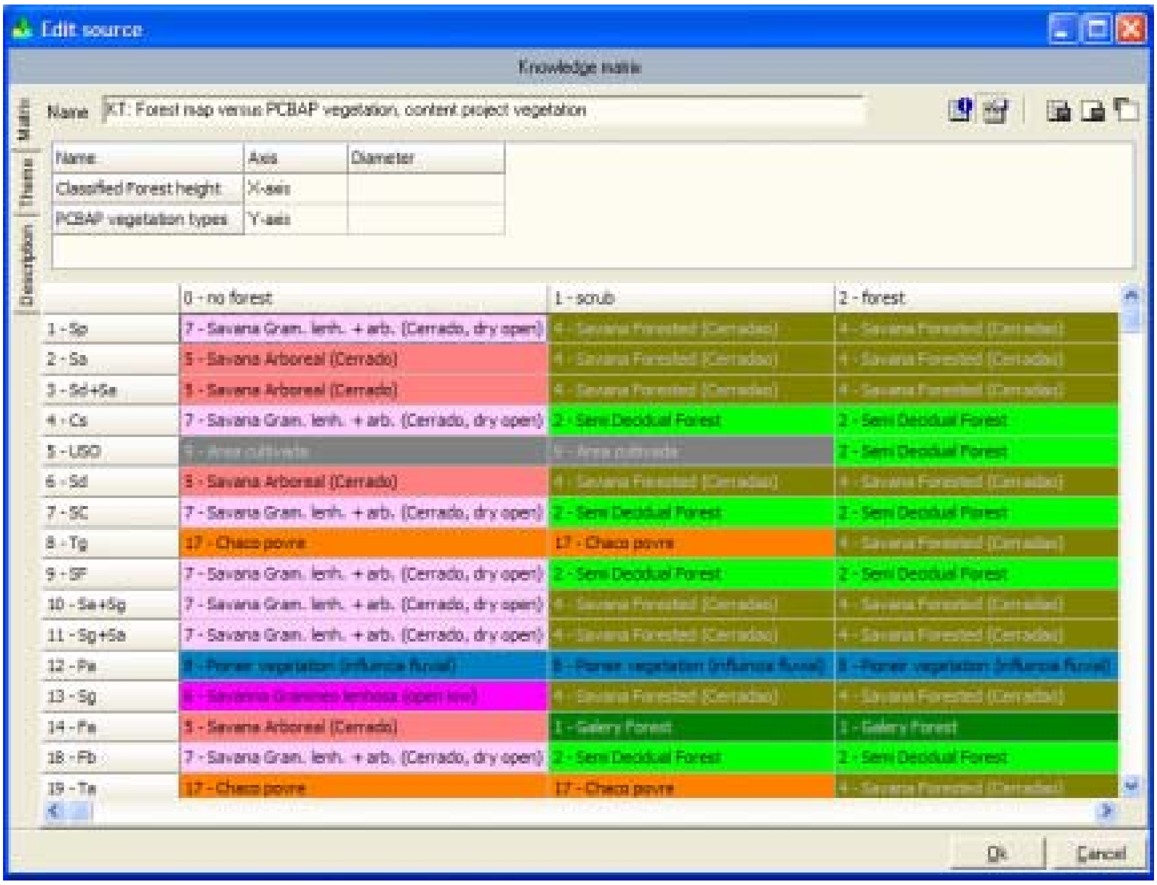
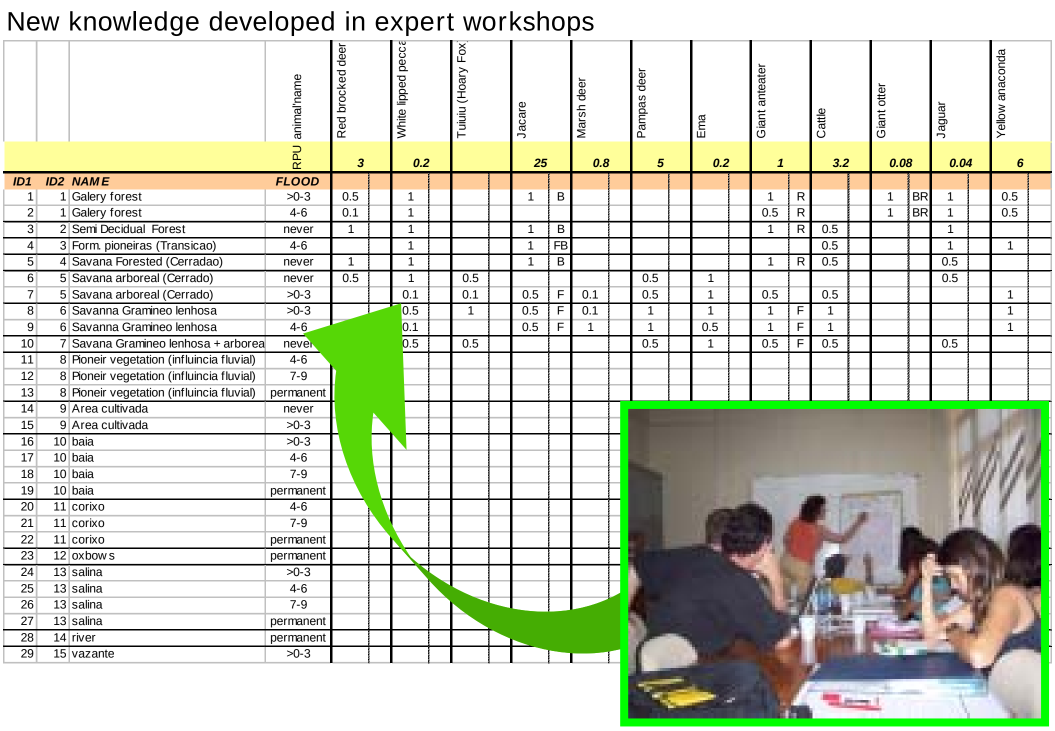


Figure 6.7 – Example of a knowledge table in LEDESS-Pantanal

Important basic data

- 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)


New knowledge developed in expert workshops

ID1	ID2	NAME	RPU animal'name / FLOOD	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				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															

Case: Creating a calculation scheme

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, the case has been build to determine how the ecotopes will change when abiotic parameters like flooding frequency will change. An other part of the case describes the impact or effect on fauna on these changed ecotopes.

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.
The calculation scheme contains the following elements:

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

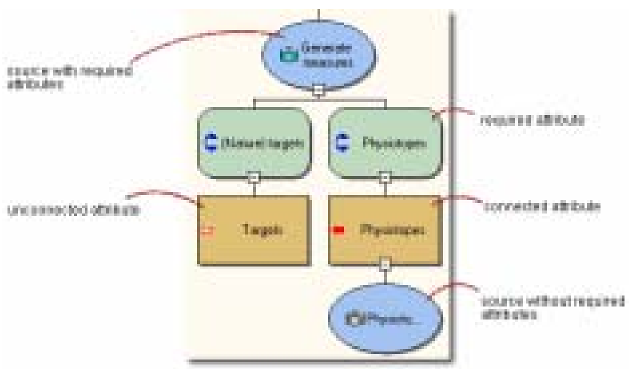


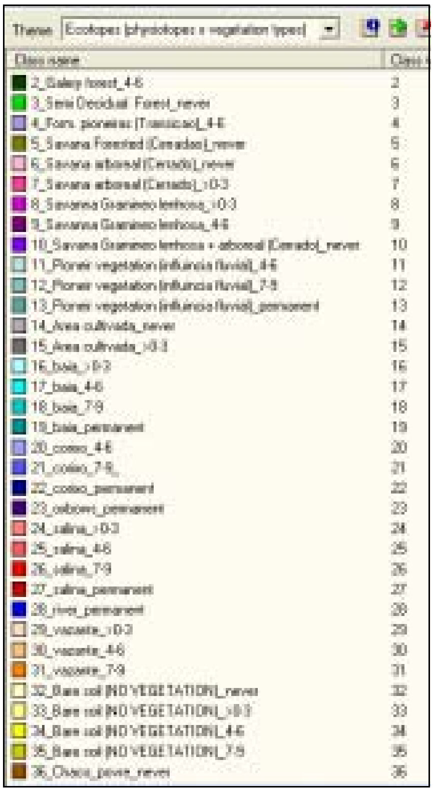
Figure 6.8 – example of elements in the calculation scheme

Case of the LEDESS-Pantanal model

The case of the LEDESS-Pantanal model consist of five important parts

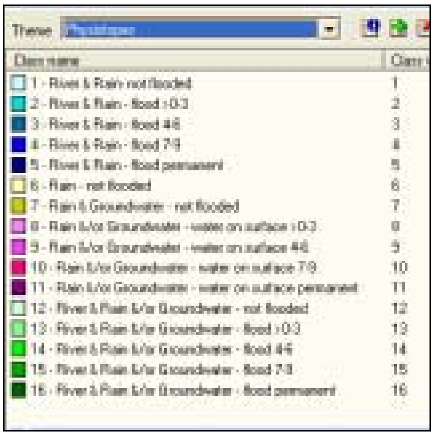
1. Creation of a final vegetation map
2. Creation of a final physiotope map
3. Aquatic ecotopes
4. Combining 1-3 to final ecotopes
5. habitat suitability of ecotopes for fauna

The typology of the used model attributes has been developed in two workshops in Brasil:
The typology final vegetation, physiotopes and ecotopes:

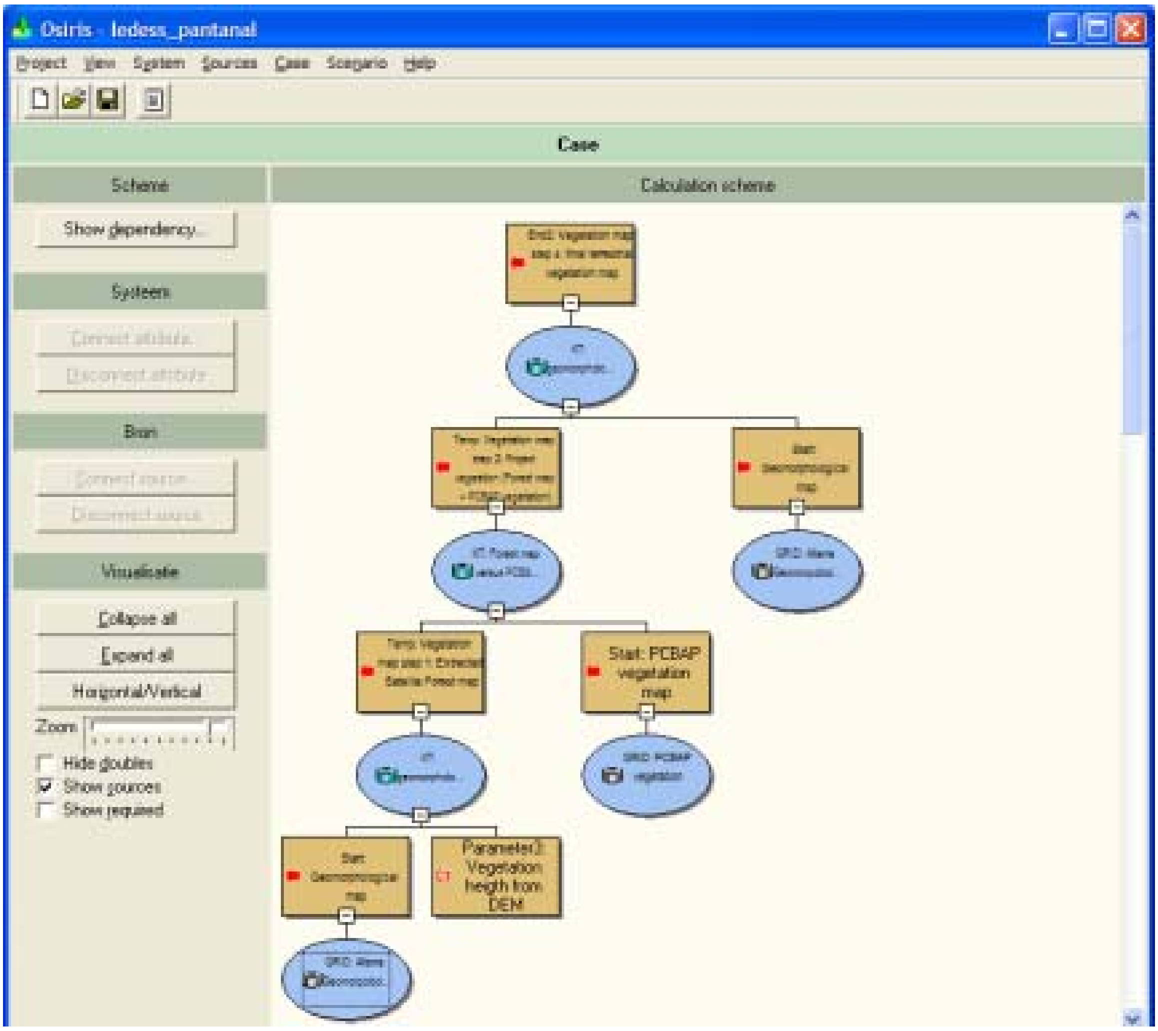


ecotopes

vegetation types



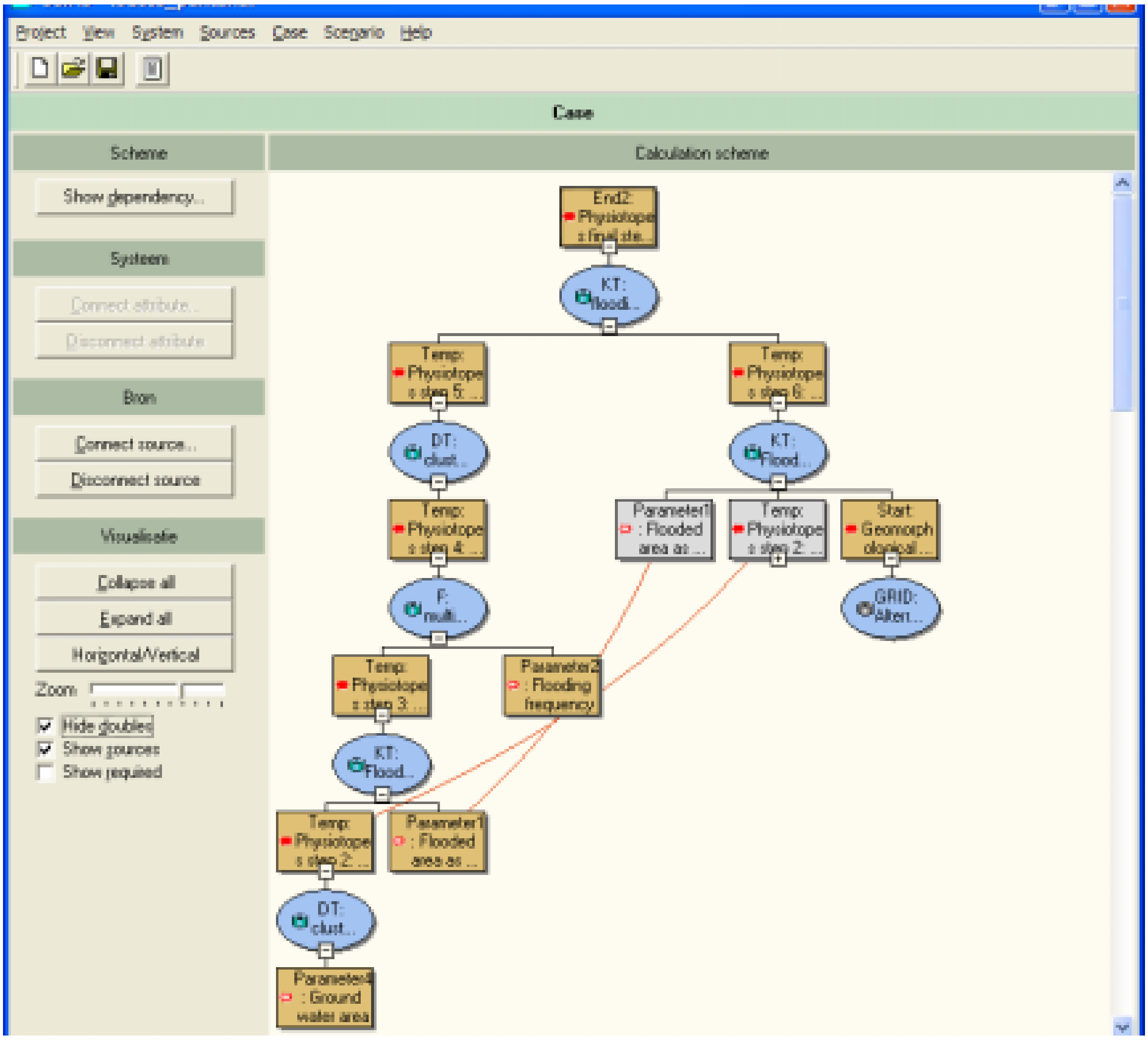
physiotopes



Developing the Final vegetation map

Final vegetation created from:

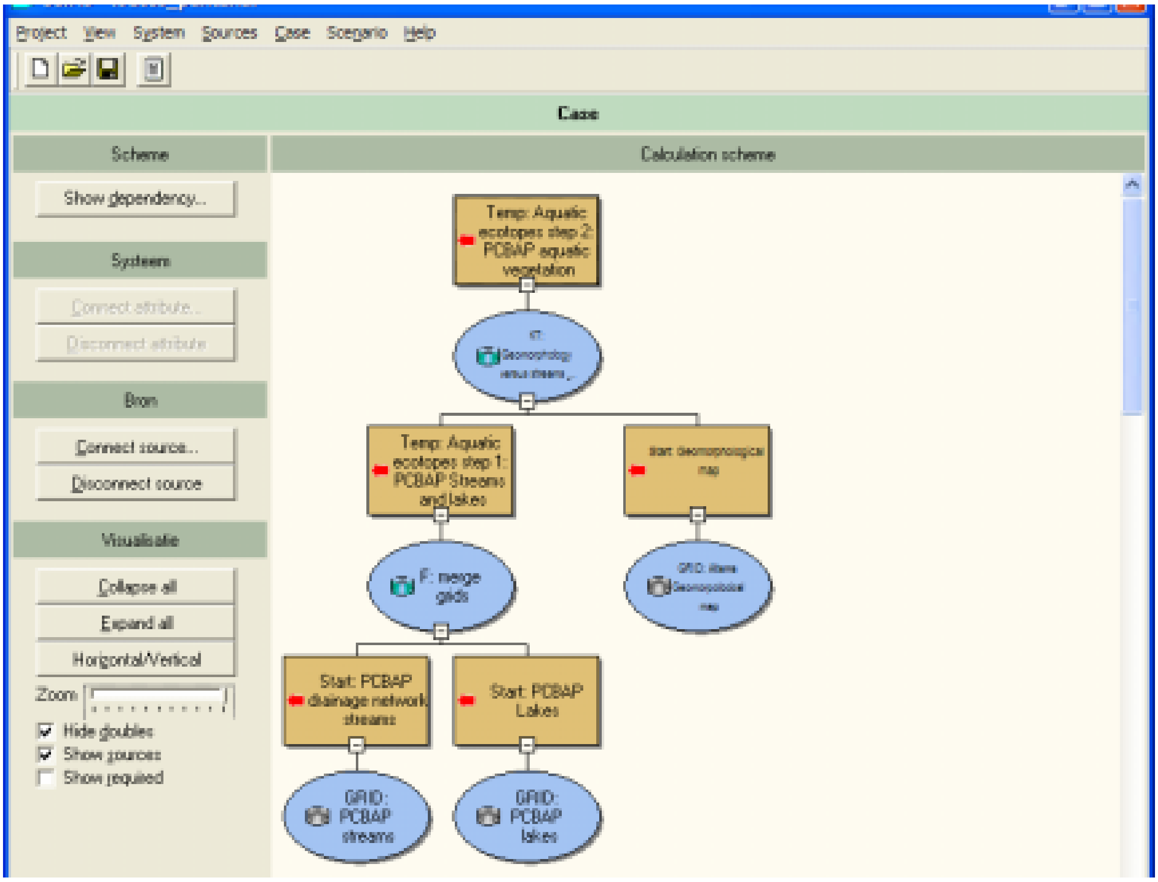
- vegetation height DEM (parameter)
- Geomorphologic map (forest type, bare soil)
- PCBAP vegetation map (basic vegetation types)



Developing the Final physiotope map

Final physiotopes (flood duration and type) created from:

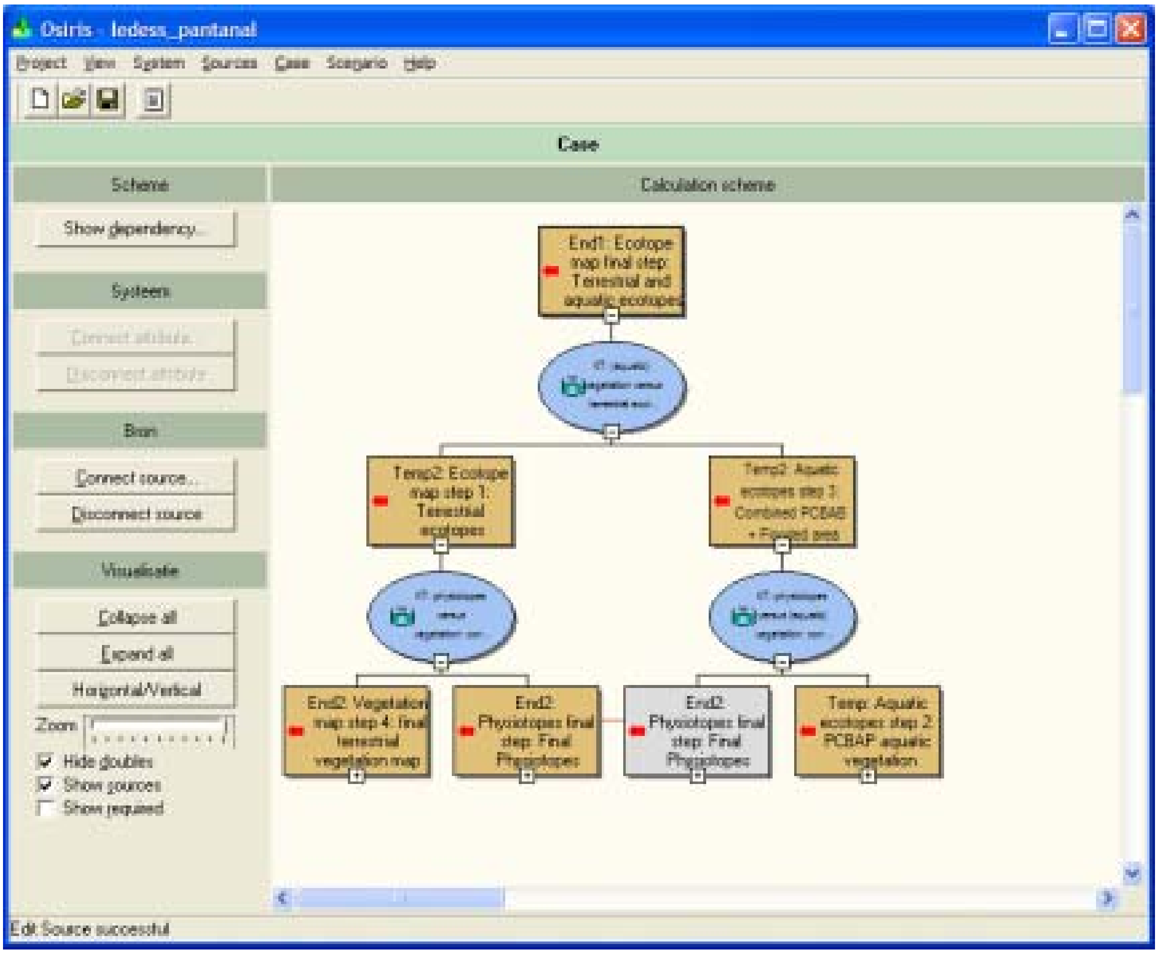
- Groundwater map (parameter)
- Maximum flooded area (parameter)
- Flooding frequency (parameter)
- Geomorphologic map (water type in combination with groundwater and flood frequency)



Developing the aquatic ecotope map

Final aquatic ecotopes created from:

- Drainage network
- Lakes
- Geomorphologic map (types)



Case for final ecotope map

Final ecotopes created from:

- Aquatic ecotopes
- Final Vegetation map
- Final Physiotope map

6.4 Scenarios and impact modelling

A scenario is called the total of external settings in a case. A scenario is based on a case. To calculate a scenario, you have to connect Esri grid sources (Parameter data) to the necessary attributes which are not yet connected.

In the *scenario* worksheet, scenarios can be defined and result maps calculated. To define a scenario, you have to connect the unconnected system attributes in the dependency scheme (which has been defined in the *case*) to scenario specific sources

Scenario parameters

Ecotope scenarios

Scenarios in LEDESS Pantanal are based on variations in flooding frequency. Final goal is to calculate the impact on fauna. Scenarios calculated:

1. Current situation scenario
2. Permanent flooding (more wet) scenario
3. More dry scenario

4. Combinations/measures like closing avulsions

Impact modelling Pantanal scenarios on Fauna

This last part of the LEDESS Pantanal model determines the suitable habitats and potential fauna populations (indicator species), based on vegetation structure, spatial requirements and additional land use. The module must be applied for each scenario, for as many animal groups and time periods (vegetation development steps) as required, producing as many maps.

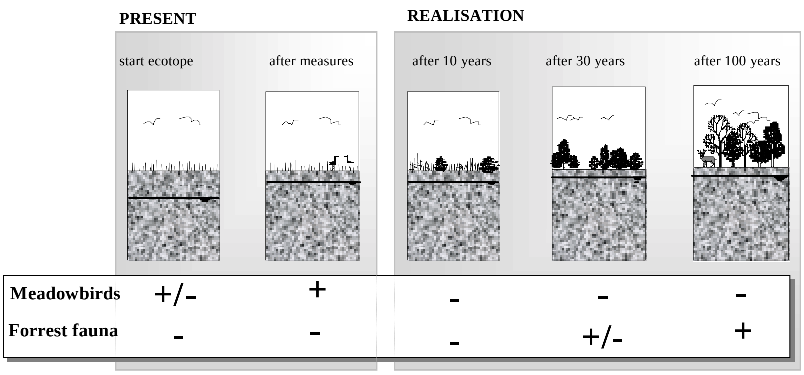
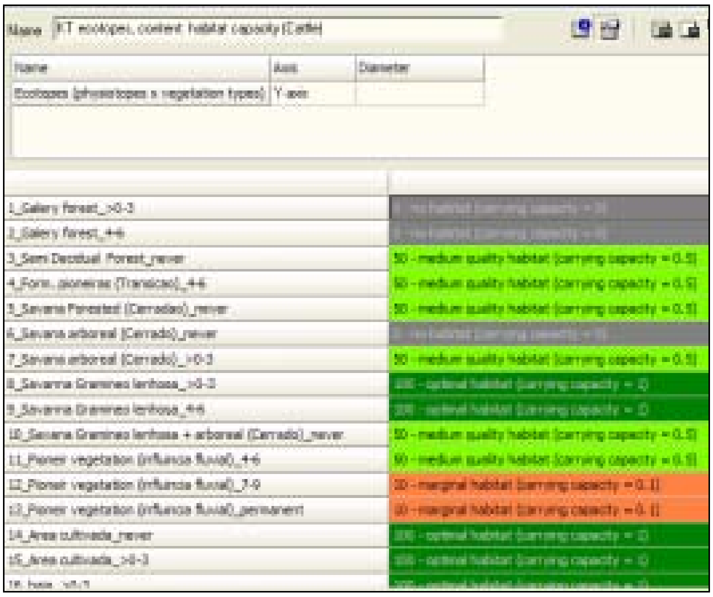
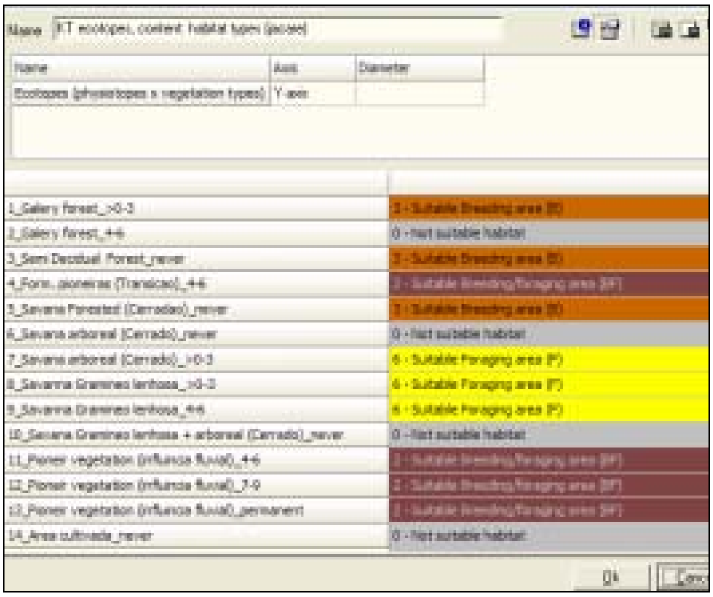


Figure 6.9 Concept of the Habitat-impact of changing ecotopes



example habitat capacity ecotopes cattle



example habitat types ecotopes jacare

Fish ecology

The workshop on aquatic species has been very productive. It has created a structure for further analysis, and that can already be seen as an important output of the project. However, it is concluded that, in the present Pantanal Taquari project, it is too early for making a LEDESS model for fish species, because food-chain relations and life-cycle relations (seasonality) might be very important factors in addition to mere habitat suitability. Local fish experts might loose their confidence in modelling if they are confronted with a "precocious" erroneous fish species map based on habitat alone. The next step is to acquire further data and knowledge on food-chain relations and life-cycle relations. This might be carried out by Embrapa or some students (either Brazilian or Dutch). WL | Delft Hydraulics may give some hints for these activities, but will not engage in further ecological modelling activities in the present framework.

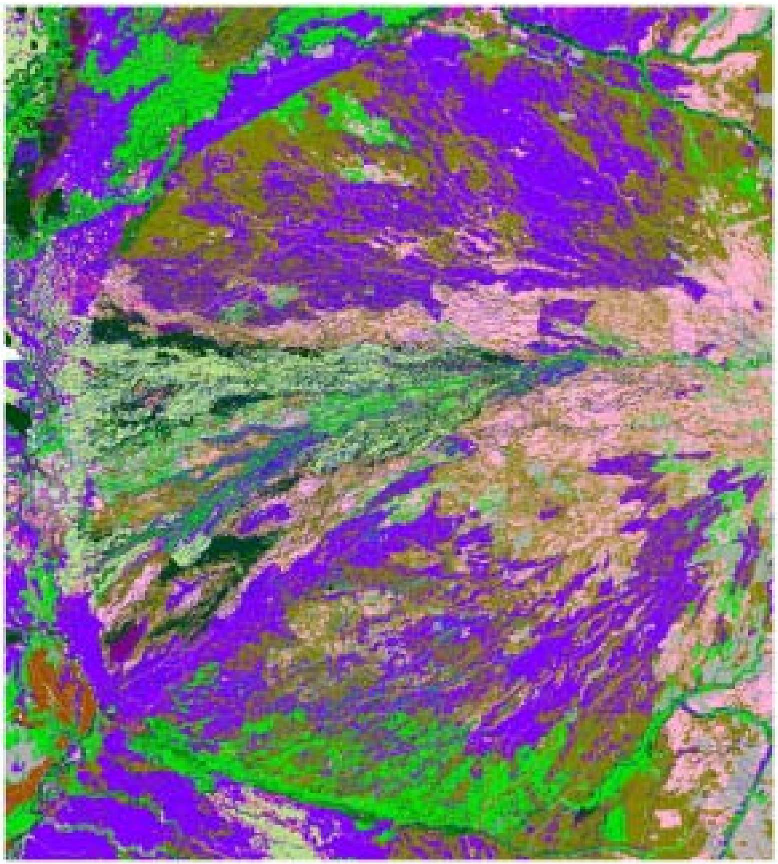
(The LEDESS model for fish species remains in stock for future follow-up projects).

6.5 Scenario results for the Pantanal-Taquari

Ecotope maps of the scenarios

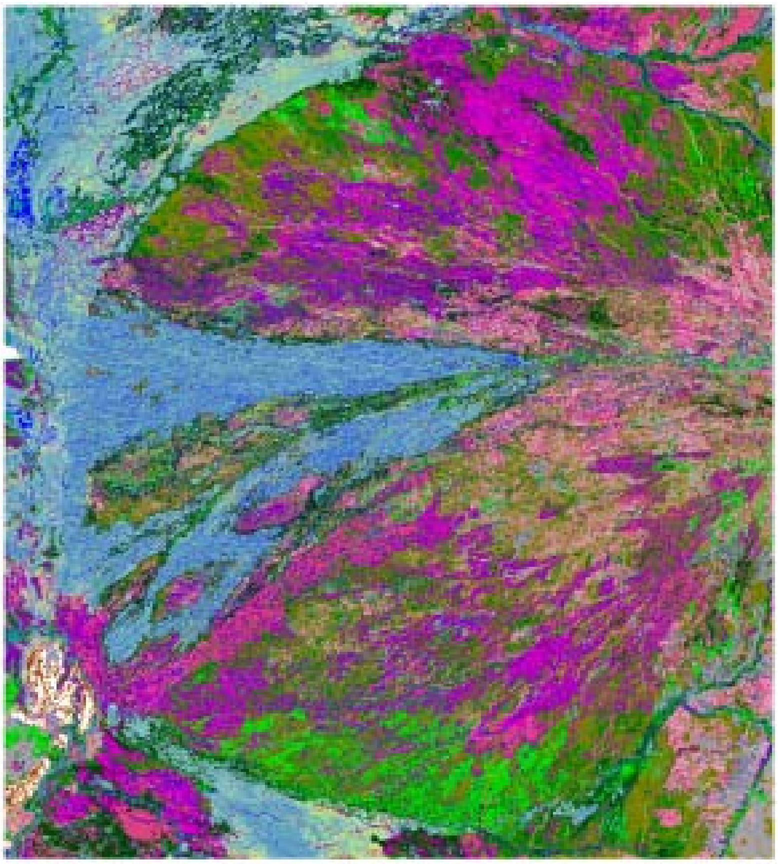
Current
ecotopes

1_Galery forest_>0-3
2_Galery forest_4-6
3_Semi Decidual Forest_never
4_Form. pioneiras (Transicao)_4-6
5_Savana Forested (Cerradao)_never
6_Savana arboreal (Cerrado)_never
7_Savana arboreal (Cerrado)_>0-3
8_Savanna Gramineo lenhosa_>0-3
9_Savanna Gramineo lenhosa_4-6
10_Savana Gram. lenhosa + arb. (Cerr)
11_Pioneir vegetation (fluvial)_4-6
12_Pioneir vegetation (fluvial)_7-9
13_Pioneir vegetation (fluvial)_perm.
14_Area cultivada_never
15_Area cultivada_>0-3
16_baia_>0-3
17_baia_4-6
18_baia_7-9
19_baia_permanent
20_corixo_4-6
21_corixo_7-9_
22_corixo_permanent
23_oxbows_permanent
24_salina_>0-3
25_salina_4-6
26_salina_7-9
27_salina_permanent
28_river_permanent
29_vazante_>0-3
30_vazante_4-6
31_vazante_7-9
32_Bare soil (NO VEGETATION)_never
33_Bare soil (NO VEGETATION)_>0-3
34_Bare soil (NO VEGETATION)_4-6
35_Bare soil (NO VEGETATION)_7-9
36_Chaco_povre_never
99_not possible



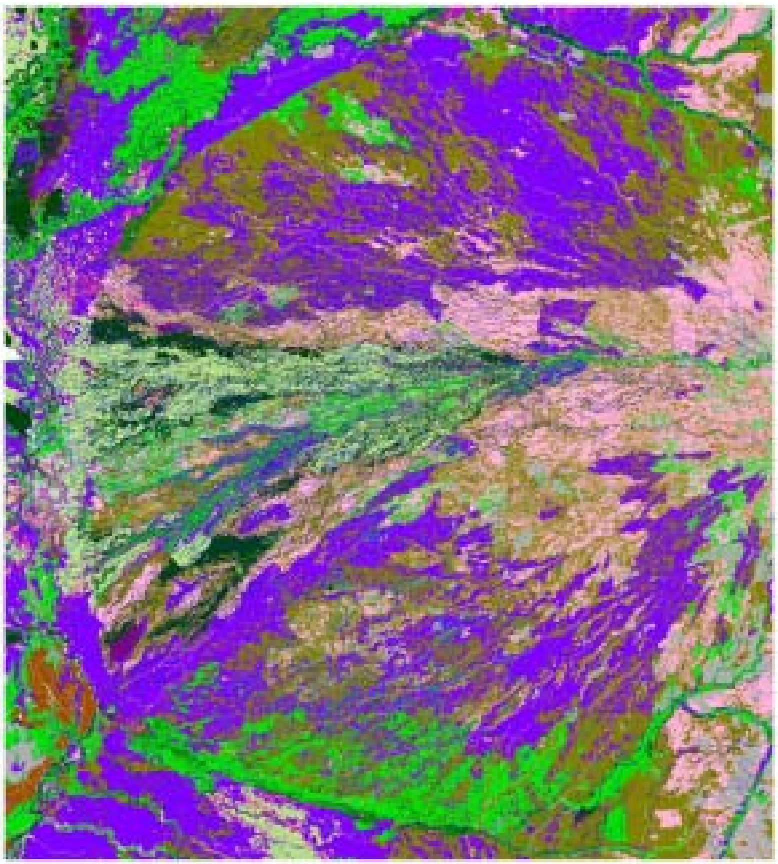
Permanent
scenario ecotopes

1_Galery forest_>0-3
2_Galery forest_4-6
3_Semi Decidual Forest_never
4_Form. pioneiras (Transicao)_4-6
5_Savana Forested (Cerradao)_never
6_Savana arboreal (Cerrado)_never
7_Savana arboreal (Cerrado)_>0-3
8_Savanna Gramineo lenhosa_>0-3
9_Savanna Gramineo lenhosa_4-6
10_Savana Gram. lenhosa + arb. (Cerr)
11_Pioneir vegetation (fluvial)_4-6
12_Pioneir vegetation (fluvial)_7-9
13_Pioneir vegetation (fluvial)_perm.
14_Area cultivada_never
15_Area cultivada_>0-3
16_baia_>0-3
17_baia_4-6
18_baia_7-9
19_baia_permanent
20_corixo_4-6
21_corixo_7-9_
22_corixo_permanent
23_oxbows_permanent
24_salina_>0-3
25_salina_4-6
26_salina_7-9
27_salina_permanent
28_river_permanent
29_vazante_>0-3
30_vazante_4-6
31_vazante_7-9
32_Bare soil (NO VEGETATION)_never
33_Bare soil (NO VEGETATION)_>0-3
34_Bare soil (NO VEGETATION)_4-6
35_Bare soil (NO VEGETATION)_7-9
36_Chaco_povre_never
99_not possible



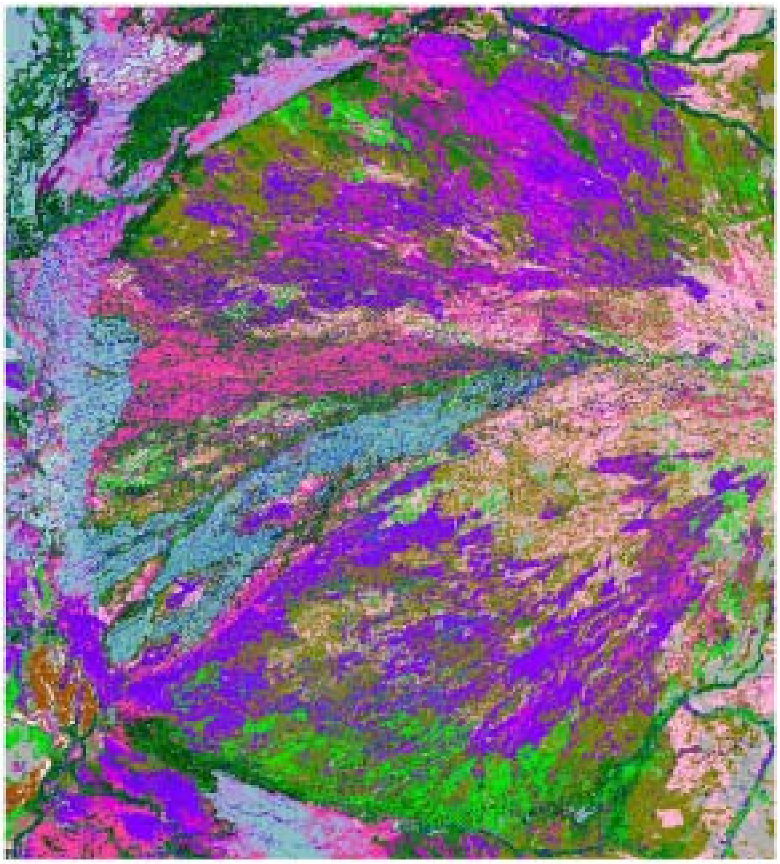
Dry ecotopes

1_Galery forest_>0-3
2_Galery forest_4-6
3_Semi Decidual Forest_never
4_Form. pioneiras (Transicao)_4-6
5_Savana Forested (Cerradao)_never
6_Savana arboreal (Cerrado)_never
7_Savana arboreal (Cerrado)_>0-3
8_Savanna Gramineo lenhosa_>0-3
9_Savanna Gramineo lenhosa_4-6
10_Savana Gram. lenhosa + arb. (Cerr)
11_Pioneir vegetation (fluvial)_4-6
12_Pioneir vegetation (fluvial)_7-9
13_Pioneir vegetation (fluvial)_perm.
14_Area cultivada_never
15_Area cultivada_>0-3
16_baia_>0-3
17_baia_4-6
18_baia_7-9
19_baia_permanent
20_corixo_4-6
21_corixo_7-9_
22_corixo_permanent
23_oxbows_permanent
24_salina_>0-3
25_salina_4-6
26_salina_7-9
27_salina_permanent
28_river_permanent
29_vazante_>0-3
30_vazante_4-6
31_vazante_7-9
32_Bare soil (NO VEGETATION)_never
33_Bare soil (NO VEGETATION)_>0-3
34_Bare soil (NO VEGETATION)_4-6
35_Bare soil (NO VEGETATION)_7-9
36_Chaco_povre_never
99_not possible

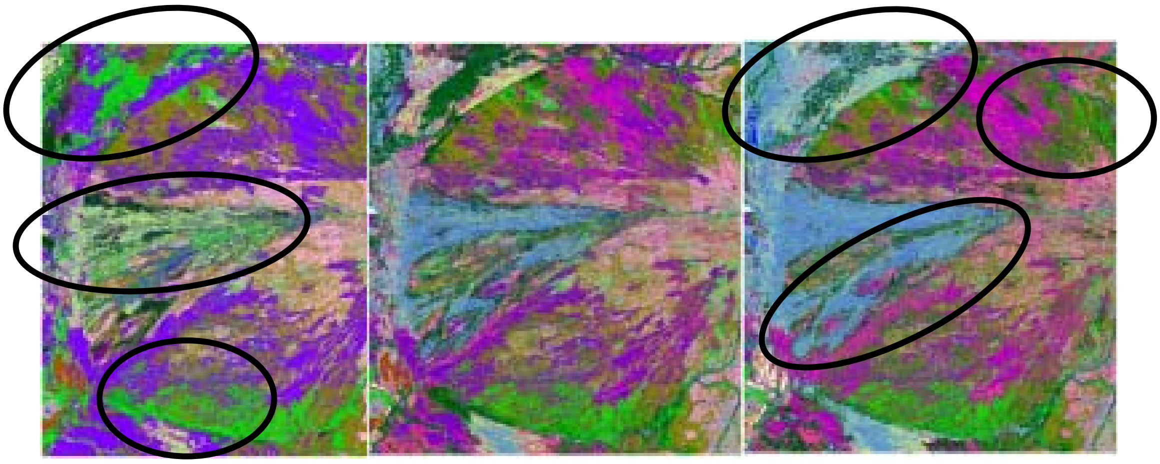


Closing no dredging

1_Galery forest_>0-3
2_Galery forest_4-6
3_Semi Decidual Forest_never
4_Form. pioneiras (Transicao)_4-6
5_Savana Forested (Cerradao)_never
6_Savana arboreal (Cerrado)_never
7_Savana arboreal (Cerrado)_>0-3
8_Savanna Gramineo lenhosa_>0-3
9_Savanna Gramineo lenhosa_4-6
10_Savana Gram. lenhosa + arb. (Cerr)
11_Pioneir vegetation (fluvial)_4-6
12_Pioneir vegetation (fluvial)_7-9
13_Pioneir vegetation (fluvial)_perm.
14_Area cultivada_never
15_Area cultivada_>0-3
16_baia_>0-3
17_baia_4-6
18_baia_7-9
19_baia_permanent
20_corixo_4-6
21_corixo_7-9_
22_corixo_permanent
23_oxbows_permanent
24_salina_>0-3
25_salina_4-6
26_salina_7-9
27_salina_permanent
28_river_permanent
29_vazante_>0-3
30_vazante_4-6
31_vazante_7-9
32_Bare soil (NO VEGETATION)_never
33_Bare soil (NO VEGETATION)_>0-3
34_Bare soil (NO VEGETATION)_4-6
35_Bare soil (NO VEGETATION)_7-9
36_Chaco_povre_never
99_not possible



Wet and current scenario major changes



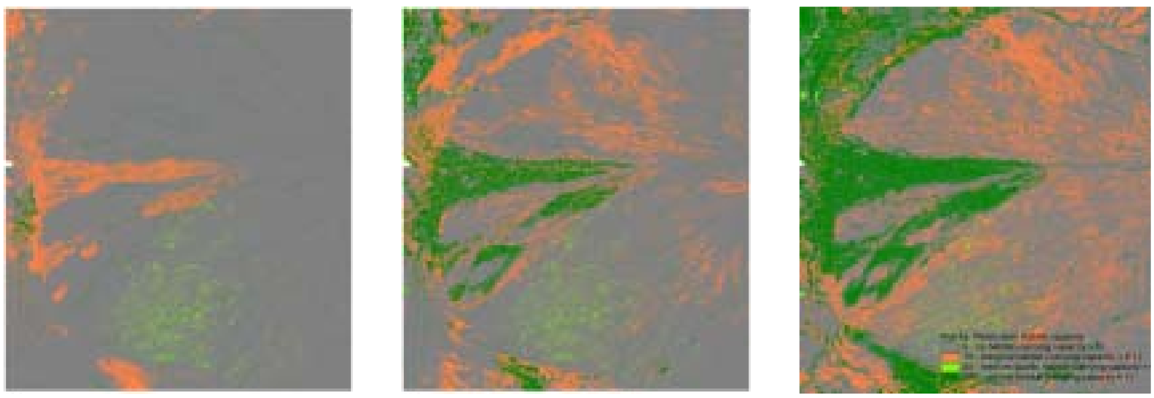
Dry | Average | Permanent flooded

- pioneer vegetation in the Caronal
- dryer forest other type savannah

- More flooding in south, northwest
- Wet forest on fan

Scenario impact habitat quality fauna

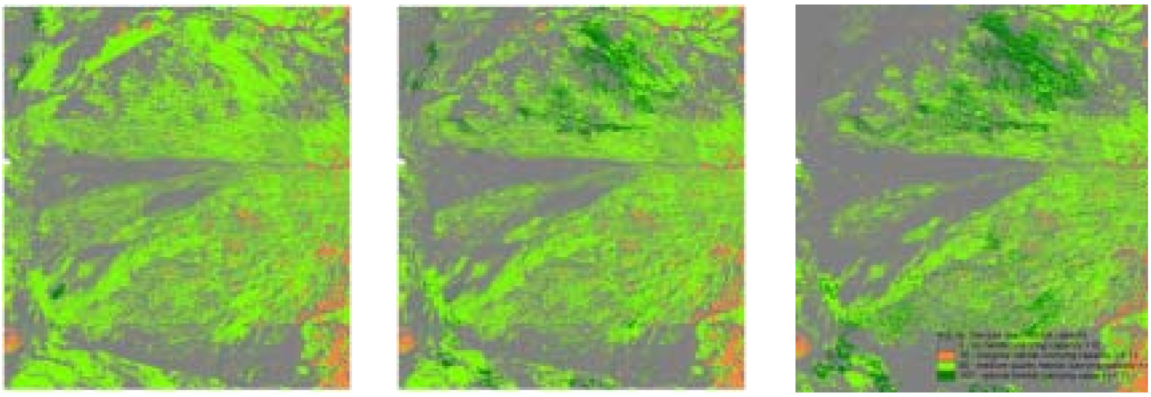
Potential habitat quality marsh deer



Dry | Average | Permanent flooded

Habitat capacity
- 0 - no habitat (carrying capacity = 0)
- 10 - marginal habitat (capacity = 10%)
- 50 - medium quality habitat (capacity = 50%)
- 100 - optimal habitat (capacity = 100%)

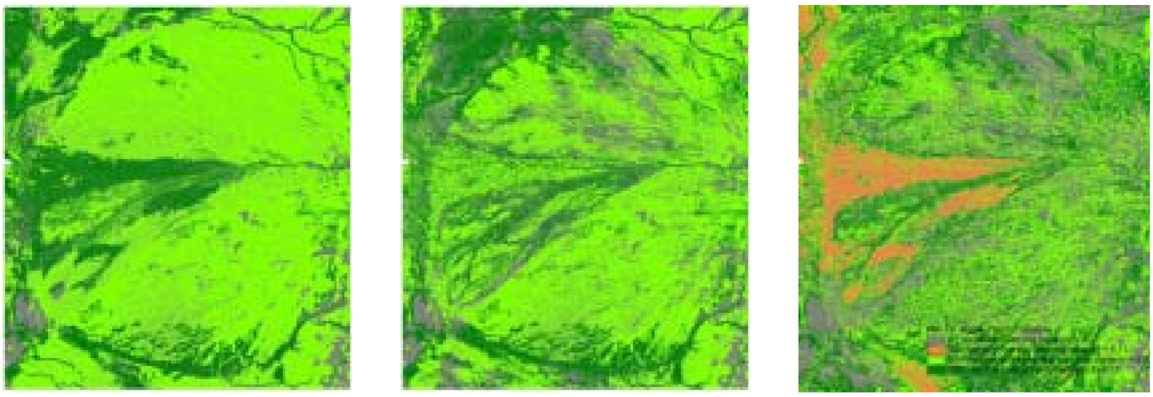
Potential habitat quality pampas deer



Dry | Average | Permanent flooded

Habitat capacity
- 0 - no habitat (carrying capacity = 0)
- 10 - marginal habitat (capacity = 10%)
- 50 - medium quality habitat (capacity = 50%)
- 100 - optimal habitat (capacity = 100%)

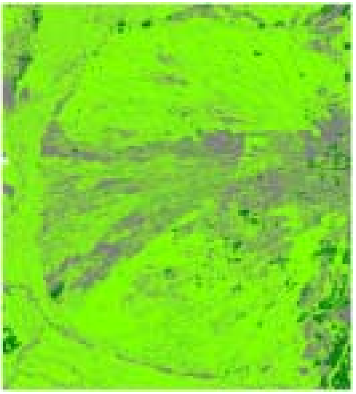
Potential habitat quality Jaguar

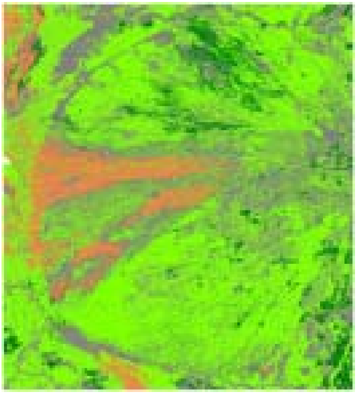


Dry | Average | Permanent flooded

Habitat capacity
- 0 - no habitat (carrying capacity = 0)
- 10 - marginal habitat (capacity = 10%)
- 50 - medium quality habitat (capacity = 50%)
- 100 - optimal habitat (capacity = 100%)

Potential habitat quality cattle





Dry

Average

Permanent flooded

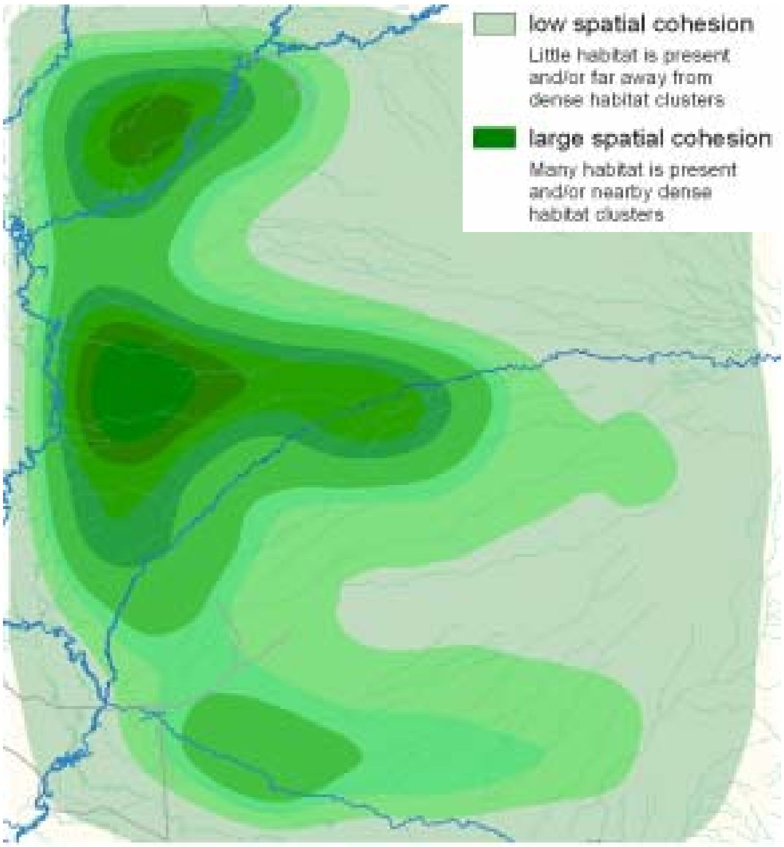
LARCH model Cohesion of habitats

Result Jaguar

Spatial cohesion of the habitat of Jaguar in the present situation.

based on amount of habitat present and dispersal capacity.

It illustrates that the habitat and
potential populations are concentrated
In three core areas.



6.6 Conclusions

Model:

- Good representation of current species abundance
- Change in flooding Ą change in vegetation pattern Ą change in quality fauna
- Calculating potential impact scenarios on fauna can be done quick
- Not all data available for spatial modelling fish (e.g. stream velocity)

Scenarios:

- Permanent flood less favourable for most species
- Very big differences between species Ą normal !
- The 2 most extreme scenarios (permanent flood & more dry) biggest impact. Rest scenarios in between these scenarios

Future should be done:

- Spatial aquatic data (may be smaller area to be more specific)

7. Socio-economic aspects stakeholders and decision making

Stakeholders 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. This has led to the problem statement in chapter 1.

In later phases the contact with stakeholders and authorities invoilved has been maintained through direct contact (ANA, Secretario de Recursdos Hídricos) and stakeholder meetings. A workshop has been organized with individual knowledge bearers from the region. These participated 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.

Interviews have been held in the streets of Corumbá to develop insight for everyone in the visions and ideas of the people in the street. 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 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…

In 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. Mario Dantas had specially invited by us, because he was the person who brought us together to work on this problem. Interviews have been given to the TV station GLOBO News (Mato Grosso do Sul). Later on the day also the newspaper Noticias do Estado called for a telephone interview.
Programme:

1. Introduction, Dra Emiko Kawakami de Resende (director Embrapa Pantanal)
2. The food aquatic chain and the flood pulse in the lower Taquari, Emiko Kawakami de Resende (Embrapa)
3. The inundations of the Taquari river: monitoring and causes, Carloa Padovani (Embrapa), Ben Maathuis (ITC), Chris Stolker (WL|Delft Hydraulics), Bob van Kappel, (WL|Delft Hydraulics), Bart Makaske (Alterra).
4. Overview of the socio-economic data of the farms that have been affected y inundations. Carlos Padovani (Embrapa), Luciana Jorge (Embrapa) and Magnolia Gomes (Embrapa).
5. Hydrological modelling of the Rio Taquari (groundwater and surface water) Erik Querner (Alterra), Remco Jonker (University Twente) and Carlos Padovani (Embrapa)
6. Impact of the inundations on the ecology of the alluvial fan of the Rio Taquari. Walfrido Tomas (Embrapa), Emiko Kawakami de Resende (Embrapa) and Michiel van Eupen (Alterra)
7. Concusions from the project and recommendations based on the results of the presented research en socio-economic analyses Rob Jongman (Alterra), Carlos Padovani (Embrapa), Luc Boerboom (ITC) and Helena Berends (Regenboog)

After that 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 cachment. 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 2 years work.

In the evening the SIMPAN (symposium on sustainable development of the Pantanal) was opened in a mix of political social and scientific activities. This symposium will last until the weekend.

Training of EMBRAPA and university staff on spatial decision support methodology.

Training was very successful. Both staff from EMBRAPA and the university were very enthusiastic about concepts of spatial decision support systems discussed. Sessions were even extended into the afternoons 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 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 (a) common problem(s) 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 problem(s).

Table 7.1. List of alternatives

Watershed scale alternatives

- Business as usual
- Closing side channel
- Stop erosion in the highlands
- Impact barriers: paved roads
- Hidrovia Paraguay
- More floods and precipitation (scenario)
- Less cattle more fire (impact)
- Dredging Taquari
- Dam at Coxim
- Organized maintenance (river management)
- Financial compensation for farmers
- National park
- Help Coronal river form its bed
- Improve cattle production

Corumba/Pantanal development alternatives

- Industrial development
- Conservation development
- Tourist development

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 7.1) using the habitat capacity data generated by the Panatanal Ledess model. Three scenarios as developed by Michiel van Eupen (a 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 7.1).

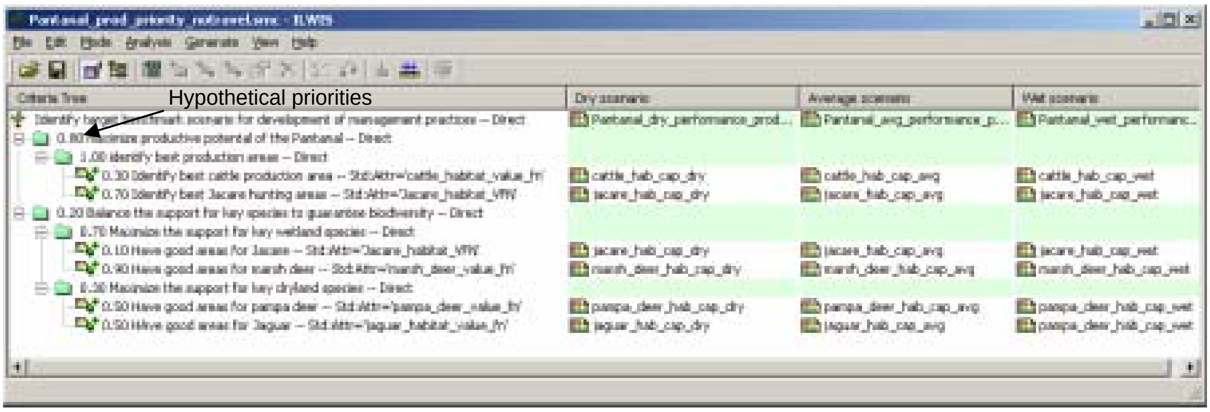


Figure 7.1. Hypothetical decision problem structure, to evaluate performance of the Pantanal under three different hydrologic conditions.

Also, hypothetical value functions (table 7.1) 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 7.1. 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 hypothetical example lead to a spatial evaluation of overall performance of the Pantanal alluvial fan area under different hydrological conditions (Figure 7.2). Due to the structuring of the problem the wet conditions are preferred, because this hypothetical (!) analysis assumes Jacare hunting areas to be of main interest

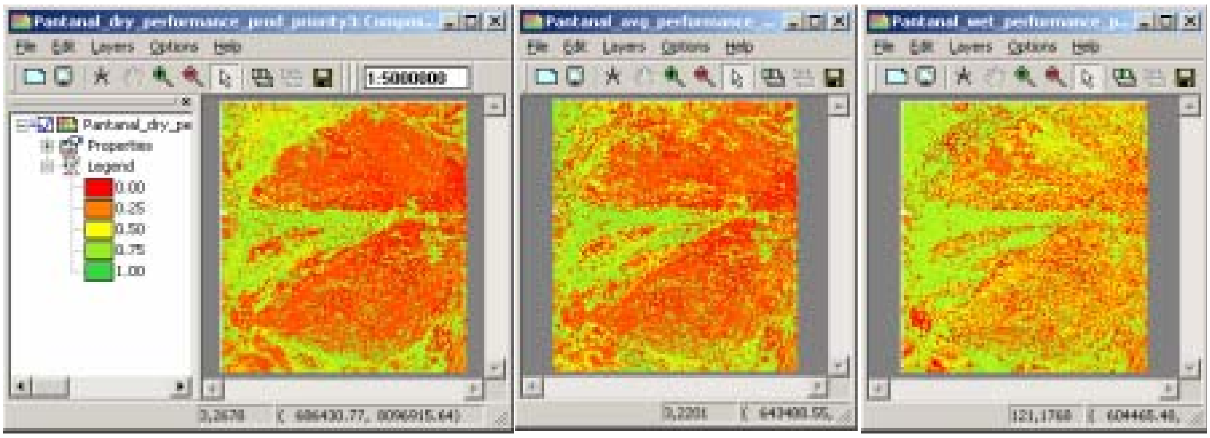


Figure 7,2. Overall performance of the Pantanal alluvial fan area under different hydrological scenarios (dry, average, and wet). Green areas perform well and red areas perform poorly, given the criteria structure, the prioritization of criteria and assessment of value functions.

1. Establish alternative criteria trees with various stakeholders to evaluate management options for the Tuaqari river. (morning 3 & 4)

Of the 30 invitees some 10 attended and some people who attended the 3rd morning did not attend the 4th, and vice versa. This really constrained the impact of these sessions and prevented the research activity to take place in which the idea was to elicit the various criteria structures present amongst stakeholders with respect to three alternatives (closing avulsions, dredging Taquari river,).

By discussing a Malaysian decision case (choice of three light rail networks) where a clear decision unit had been defined, the efficiency and necessity of a decision unit and decision support systems could be demonstrated. In the Malaysian case people argued a long time about objectives, wishes, alternatives etc. but after performing the analysis as a decision unit, it appeared that the same alternative was best for everyone, yet for different reasons. The take home message was that without a decision unit is possible to get solutions to a problem, however they may not be the right solutions to the right problem. In other words, no design criteria exist for the solutions. Before solutions are to be developed through value-based development, using the values that are going to be used in evaluation and choice.

The exercise was presented as a “cleaning of the house”. We needed to define a controllable problem to which we three alternative solutions (see above). The last day when we wanted to start with development of an evaluation structure, started with a long discussion with one of the farmers, who angrily walked out the room. The farmer was angry that still no solutions were presented. The situation was very well managed and contained by Carlos Padovani. With the remaining time we a plenary session indicating how important it is to well define an evaluation structure and if that is not done, how likely it is that the wrong solutions will be developed.

Appendix: Program Pantanal workshop October 26-29, at Embrapa, Corumba, MS, Brazil

Time	Tuesday 26th	Wednesday 27th	Thursday 28th	Friday 29th
	Course on basics of spatial multi-criteria evaluation		Workshop on decision problem structuring applied to Pantanal and institutionalization of decision making process	
8:00 – 8:30	- Opening - Program Introduction - Introduction of participants	Introduction to evaluation - problem structuring by example of two stakeholders (preparation for moderation) - partial valuation	- Opening - Program Introduction - Introduction of participants	Group working session: - Review and finalize value trees from different stakeholder perspective
8:45 – 8:50	BREAK (stretching the legs)			
8:50 – 9:30	Introduction of participants (continued)	Introduction to evaluation - prioritization of criteria - aggregation to overall ranking - sensitivity analysis or the risk of making the wrong decision - spatial evaluation	- Introduction to (20 min) - method of multi-criteria evaluation and role in alternative based conflict resolution - model of sources of conflicts - **importance as decision makers to dedicate time to evaluation and steer any research**. - Identification of stakeholders and working groups (20 min) - Intro to review of alternatives (10 min)	Plenary working session: - "walk-by" presentation of value-trees - **Observations on criteria trees.**
9:30 – 10:00	BREAK (coffee)			
10:00 – 11:00	Introduction to decision support systems and scenario development	Introduction to ILWIS-SMCE software	Plenary working session: - Brainstorm 3-4 alternatives (10 min) - Discuss alternatives (40 min) - Intro to development of how to make good value trees (10 min): **be self-critical**!!!	Plenary working session: Doing an example non-spatial analysis - Use example criteria tree - Filling in data qualitatively (pairwise comparison) - Establish prioritization - Ranking from different stakeholder perspectives
11:00 – 11:05	BREAK (stretching the legs)			
11:10 – 12:15	Discussion of strategic rail network study Kuala Lumpur Malaysia	Exercise with ILWIS-SMCE software	Group working session: - Develop value trees from different stakeholder perspective in four groups	Workshop continued: Discussion about **institutionalization of scenario development and evaluation process**
	LUNCH			

8. Technical solutions, possibilities and costs

The technical possibilities for restoration of the river

- 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 capacitity building on erosion and river management
- 'Doing nothing'but buy out the inundated land

Drainage of the Taquari

The distance of the river stratch to be drained: 350 km. If a depth of 3 metre is accepted (then the river can be used for shipping) the amount of material to be dredged is 60.000.000 m^3. With the equipment available in Corumbá the time needed to do this is 10-30 anos and the costs are estimated on R$ 180.000.000 based on figures for dredging the Paraguay. This is without including the daily transport of bedload of 2000 m^3.
The consequences of drainage are that a continuous activity is started; drainage cannot be stopped without losing it effect in a relatively short time. There is need for a supervising orgainsatio, but finally the river pulse, biodiversity and populations of fish will recover. Part of the land geets relatively dryer (Figure 8.1).

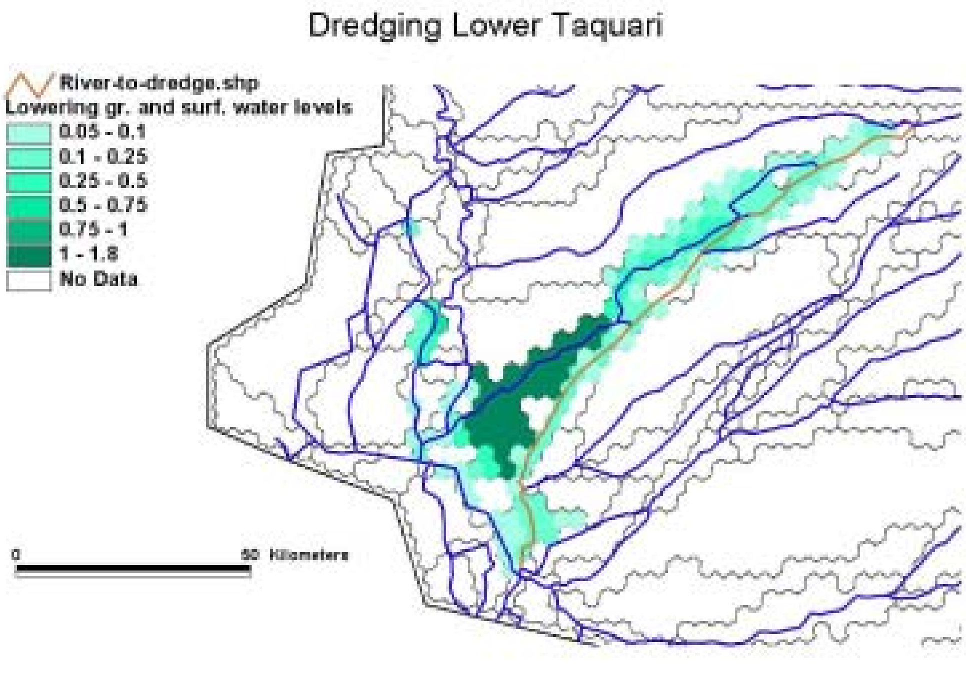


Figure 8.1 Potential lowering of the flooding drainage of the Taquari

Closing the avulsion of the Caronal

This solution can only be carried out after or in combination with the river drainage. If this is not done in combination then other areas around the existing Taquari will be flooded (Figure 8.1). For the drainage hard material must be used, because the area involved is unstable. 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.

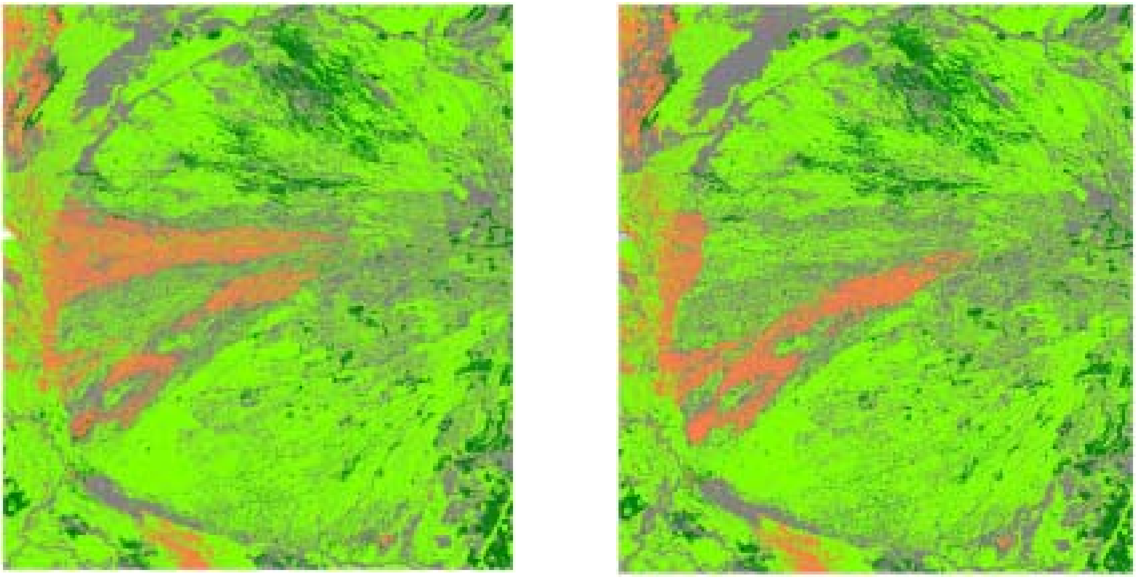


Figure 8.2 Changes after closing the aavulsion of the Caronal (left before closing, right after closing)

Prevent new avulsions

The instable zone is downstream of Figueiral and is 300 km long. Prevention is a continuous activity and should be supervised by a management organization. New avulsions can be natural or illegal. It is no well possible to estimate costs. 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 continues

Help the river to create a new river bed from Caronal westward

The distance is about 230 km. It a depth of 3 m is taaken then bout 80.000.000 m^3 should be excavated. The time needed is depending on the equipment available 10-30 years and the costs R$ 240.000.000.
The consequences are less inundations in this part of Paiagua but the old riverbed will dry out.

Construction of dikes

The subsoil consists of highly erosive and instable material. De material needed for stable dikes is not available and should be brought in from elsewhere. Therefore this solution is not considered realistic.

Construction of a dam in the Planalto

Dam construction for retention of sediment c abe done on one place oro n several places. The more places are selected the lower the dam can be. If the dam is used for other functions as well, such as water storage or electricity production, then the dam should be much higher and more expensive. Estimated costs are

- For a dam for water retention (40 m high) and sediment retention R$ 1.400.000.000 (base don a comparable dam in Argentina (Figure 8.3)
- For a dam for sediment retention (10 m high) only R$ 20.000.000
- 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. If there is only one dam, then the flood pulse and fish migration will disappear or be severely hampered. Three smaller dams will have less impact on the flood pulses.

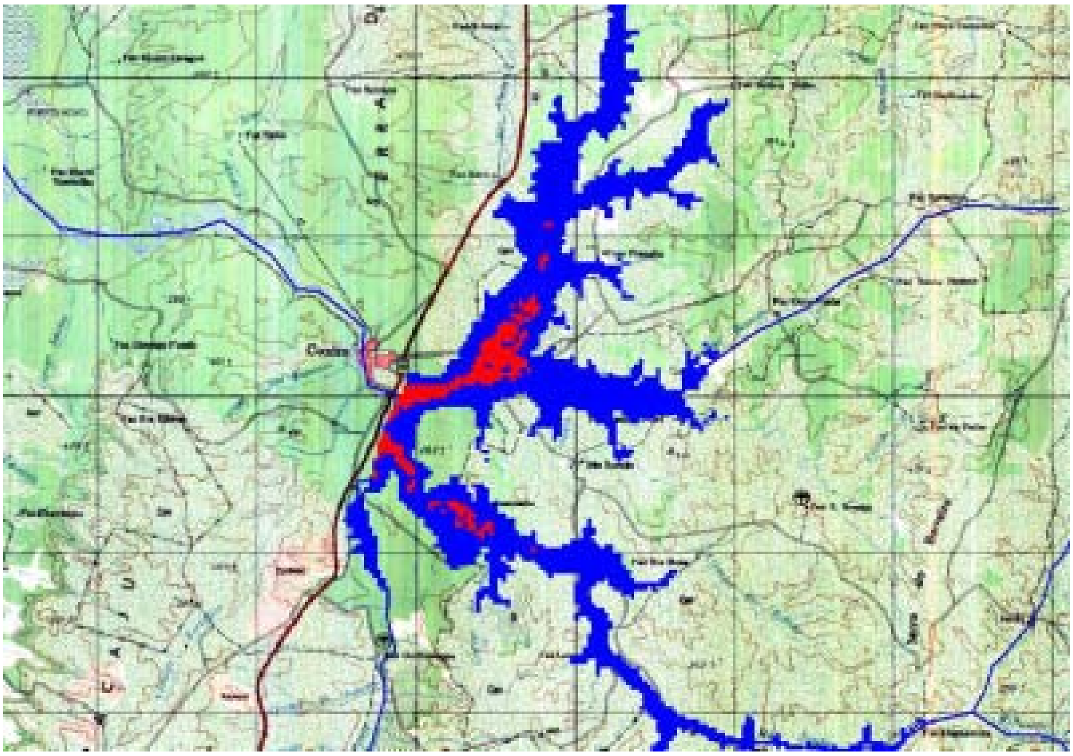


Figure 8.3. Dam for water and sediment retention. Red: only sediment (10 m), blue: water and sediment (40 m)

Prevention of erosion through afforestation of river margins on the Planalto

The Codígo Florestal obliges to keep 10% of the land forested. For the Planalto this would mean2.700 km^2. This requires planning and supervision. Also it is needed that the farmers on the Planalto need pumps to prevent cattle to go to the water. Estimated costs are R$ 8.000.000
The consequences are a decease in ersion and decrease in potential discharge due to increased evapotranspiration.

Prevention of erosion through through capacity building and river management organisation

River management organization is a long term solution. Capacity building is in for long term solutions. 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.

Develop a National Park

In this case the inundated area of maximum of 11.000 km^2 should be compensated. Farmers should be bought out. It is a short quick solution for the farmers and a long term solution for biodiversity. For full compensation costs between R$ 100.000.000 to R$440.000.000

Recommendations

- Develop na organisation for river management.
- Prevent erosion on the Planalto by application of the código florestal for the river edges.
- Compensate the farmers for the flooding by creating a National Park.
- Eventual construct some small dams for sediment trapping when needed.

Annexes:

08 CIDADE

Projeto Taquari é discutido em Corumbá

Evento motiva sociedade a solucionar problemas

O Estado de Mato Grosso do

25 de Setembro

MEIO AMBIENTE

Recuperação do Taquari custará R$ 1,4

Embrapa Pantanal procura criar mecanismos para evitar extensão de assoreame

André Navarro

A recuperação completa do rio Taquari deve custar em torno de R$ 1,4 bilhão. O assoreamento do leito do Taquari, que provocou a inundação de 1,2 milhão de hectares, é tratado como a maior tragédia ambiental do Pantanal e também o maior problema da região.

Pantaneiros e pesquisadores discutiram o assunto numa reunião onde foram expostos os resultados de um trabalho de pesquisa e levantamento encabeçado pela Embrapa Pantanal. No encontro ficou evidente que, apesar de o rio ter recuperação, a captação de verba para que isso aconteça ainda é um grande problema.

"Temos de traçar a viabilidade econômica desse projeto, que deve durar décadas para ser concretizado", afirma o pesquisador da Embrapa Carlos Padovani.

Segundo ele, a complexidade dos trabalhos para serem desenvolvidos demanda tempo e dinheiro.

Só o desassoreamento do canal está orçado em R$ 30 milhões. Além disso, vai ter de ser feita uma barragem na cabeceira do rio para impedir que seu nascimento seja entupido pela areia. "Temos inclusive que criar um comitê para gerir essa região", frisou Padovani, alertando para o fato de que, mesmo depois de recuperado o rio, a região vai ter de ter um trabalho de acompanhamento constante para que não sofra outra tragédia ecológica.

Os estudos de recuperação do rio Taquari vêm sendo feitos há vários anos. Para viabilizar o projeto será necessário verba internacional. O assunto também vem sendo discutido pelo Ministério do Meio Ambiente, que se prontificou a procurar parceiros no Exterior para financiar o projeto.

Com o assoreamento do leito, areia formou coroa de vários trechos do rio e tornou a navegação inviável, além de alterar o cur

Brazilian river out of control

WB 29/11/2004

Aerial photo of the River Taquari in Brazil. / photo Alterra

The people living along the Taquari River in the western part of Central Brazil are regularly confronted with floods. The amount of sediment that comes with the floodwater is also enormous. A Brazilian/Dutch research team led by Alterra went in search of the natural human causes of the problem, and has now taken the first steps towards setting up a river management organisation that works.

The researchers have come to the conclusion that the main cause of the problem is a natural process of river deposition in the downstream area of the Taquari. A second important cause is the changes in vegetation on the plateaus which form the hinterland of the Taquari River. A change from dry savanna (cerrado) to grassland (for livestock rearing) has changed the ground water flows and resulted in increased soil erosion. The Taquari River is faced with much more sand to deal with and has changed from a meandering river into an unstable, weaving river that quickly silts up. It has also become very unpredictable.

Project leader Dr Rob Jongman, of Alterra: 'The most important strategy for dealing with the river will be erosion control in the upriver area, and the people are going to have to learn to adapt their ways to those of the river. This requires a management organisation. Don't forget we are talking about an area of 80,000 square kilometers and a population of over 100,000.'

One problem is that the regional governments have no say over the Taquari River. 'Each individual landowner along the Taquari does as he pleases. There is very little cohesion or cooperation.' The research team has been trying to do something to improve the situation. They have organised various meetings to try and get the various parties – governments, local population and NGOs – together. Jongman is pleased with the results so far: 'The NGOs, one of which is called Riosvivos, are now recognised by the government and we have spoken with the state departments of the Mato Grosso and the Mato Grosso do Sul regions about river management. People from the departments have visited the Netherlands and taken a course on wetlands management at RIZA, the Dutch institute for integrated freshwater management and waste water treatment. That has helped them to start working together.'

Alterra is working together with RIZA, WL/Delft Hydraulics, ITC Enschede, the engineering company Arcadis and the Brazilian agricultural institute Embrapa. The project falls under the Dutch programme Partners for Water that started in 2000. / HB