AMAZONIANA	XVII (3/4): 481-502	Kiel, Dezember 2003

Cerrado streams - characteristics of a threatened freshwater ecosystem type on the Tertiary Shields of Central South America*

by

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(Accepted for publication: October, 2003).

Abstract

Cerrado is a seasonal savanna type covering 20 % of the Brazilian territory, however in large areas its vegetation has been replaced by agriculture. The high plains of the Central Brazilian Shield are incised by a large number of stream valleys. In spite of their small individual size, the extension of the stream valleys is estimated to 5 % of the total Cerrado area. Apart from their geographical occurrence, Cerrado streams are characterized by extremely low conductivity, weak buffering capacity and variable pH values which are a consequence of the ion poverty of the soils. The hydrographs show very stable patterns during the dry season and frequently recurring flashfloods during the rainy season. The biota of Cerrado streams reveal a range of characteristics such as a reduced proportion of shredding invertebrates, large numbers of predators, and high resistance and resilience to spates. Species traits of aquatic insects include adaptations such as small body size, polivoltine life cycles and the synchronous occurrence of different larval stages. These features make them interesting objects for the development and testing of new stream concepts. On the other hand, the biota and habitat structures are highly sensitive to inputs of inorganic sediments from erosion gullies which threaten literally all Cerrado streams in the agricultural landscapes of Mato Grosso.
Keywords: **Lotic ecosystem, habitat, riparian zone, wetland, erosion, Brazil.**

Resumo

O cerrado representa um tipo de savana sazonal que cobre 20 % do território brasileiro, do qual porém grandes áreas foram tomadas pela agricultura. Os planaltos do Escudo Brasileiro são retalhados por um grande número de vales de córregos. Mesmo o tamanho dos vales individuais sendo pequeno, a sua extensão total está sendo estimada em 5 % da área total do cerrado. Além da ocorrência geográfica, os córregos do cerrado são caraterizados por uma condutividade extremamente baixa, ausência de substâncias tamponadores e baixos valores de pH devido à pobreza iônica dos solos. Os linígrafos demonstram padrões muito estáveis durante a estação da seca e freqüentes enchentes durante a estação chuvosa. Os organismos dos córregos do cerrado apresentam uma grande variedade de características como por exemplo uma pequena proporção de invertebrados do tipo triturador, um número elevado de predadores e uma alta resistência e resiliência à enchurradas. Traços específicos dos insetos aquáticos incluem adaptações como

*Dedicated to Prof. Dr. Wolfgang J. Junk on the occasion of his 60th anniversary.

ISSN 0065-6755/2003/481/ © MPI für Limnologie, AG Tropenökologie, Plön; INPA, Manaus

um corpo pequeno, ciclos de vida polivoltinas e a ocorrência sincronizada de vários estágios larvais. Estas caraterísticas fazem dos córregos do cerrado objetos interessantes para testar novos conceitos da ecologia lótica. Porém, os biotas e as estruturas de habitat são muito sensiveis às entradas de sedimentos inorgânicos derivando das voçorocas, ameaçando literalmente todos os córregos do cerrado nas paisagens agrícolas do Mato Grosso.

> *"If we cannot set aside our personal interests, research, and development, and put our entire effort to affixing permanently some of tropical nature, then we have sold the tropics' long-term fitness for a handful of instant gratification."* D. JANZEN (1985).

Introduction

Much ecological research has been done to contribute to sustainable landscape management in the tropics since Daniel JANZEN wrote these words, however the velocity by which tropical ecosystems are being destroyed has become even more scaring today and efforts for conservation of tropical ecosystems are more needed than ever. One important achievement for the advance of basic and applied tropical ecology by Wolfgang J. JUNK was the establishment of the SHIFT program, together with his Brazilian partner, Eneas SALATI. Within this cooperative program which is dedicated to ***S***tudies of ***H***uman ***I***mpacts on Forests and ***F***loodplains in the ***T***ropics (SHIFT), Brazilian ecosystems were analyzed comparing disturbed and natural habitats in order to improve impact analysis and to develop techniques for the melioration of human impacts, for the sustainable use and for the conservation of biodiversity and globally important ecosystems.

One SHIFT project was designed to study the ecology and environmental problems of the Pantanal, a large wetland in Central Western Brazil (JUNK & DA SILVA 1995; DA SILVA et al. 2001; NUNES DA CUNHA et al. 2004). Flooding in the Pantanal is partly caused by direct rainfall, however a large part of the floodwater and of the residual waterbodies during the dry season derive from the tributaries. The high plain (Planalto) is carved by a dense net of low order streams and their valleys. Due to the high stream density, they form an enormous extension in total. We estimate that 5 % of the catchment area of the Upper Paraguay is covered by streams and their riparian wetlands, which is a similar figure as the estimate for Amazonia (JUNK & FURCH 1985). The catchment areas of the feeder rivers of the Pantanal are intrinsically linked with the wetland by ecological corridors (WANTZEN & NUNES DA CUNHA unpubl.). These corridors do not only favor the gene flow of animals and plants between these meta-ecosystems, but they also convey the effects of pollution and erosion from the Planalto into the Pantanal (see Fig. 1 a-c).

One of the most severe human impacts in catchment areas of the Planalto is soil erosion (WANTZEN 1998). Most of the erosion problems came up with inadequate landuse techniques applied in an early phase of the colonization in the 1980ies (COUTO 1990), however their effects last until today (WANTZEN & NUNES DA CUNHA unpubl.). About 30 % of the catchment area of the Upper Paraguay river have been deforested until 1994, however the largest part of the deforestation (93.75 %) occurred in the Cerrado of the Planalto, which has lost 46.22 % of its natural cover (SILVA et al. 1997). Erosion occurs mainly at the sites where surface runoff can accumulate, e.g., earth roads or cattle tracks. When erosion gullies reach the groundwater level, they initiate a vicious circle of channel incision and water table lowering. Lateral pipes (groundwater macropores) increase the catchment areas of the gullies, locally called *"voçoroca"*. Gullies of over 20 m width, 10 m depth and several hundred meters length are common in the agriculturally used Cerrado area of the Planalto high plains of Central Brazil. The consequences for the biota of the stream-wetland-systems of the tributaries are deleterious. The benthic stream flora and fauna become strongly reduced (WANTZEN 1998) and the vegetation of the valley side campo wetlands severely changed. Various solutions for the problem have been proposed (RODRIGUES et al. 1999; WANTZEN 2002), however erosion control continues to be one of the major concerns of the National Water Agency (ANA).

Knowledge about the basic patterns and processes of the endangered Cerrado stream ecosystems are needed as baseline for adequate conservation concepts. In this paper, the physical and biological setting of Cerrado streams in Mato Grosso are characterized based on results of a long-term study and a definition of the stream type and a distinction from other stream types are given.

Materials and methods

Site description

The study area included streams near the highway BR 364 between São Vicente and Rondonopolis, in a distance of about 100 to 200 km southwest of Cuiabá city, the capital of Mato Grosso. Most of the first to third order streams reported here belong to the upper catchment region of the Brilhante-Tenente Amaral stream system, a tributary to the São Lourenço River, which is one of the major feeder rivers of the Northern Pantanal (see Fig. 1a). We abbreviated the regularly studied streams as follows: Formoso (FOR), Ajuricaba (AJU), Felipe (FEL), Caité (CAI) and Córrego Tenente Amaral (CTA). The watershed of the Tenente Amaral stream (GPS reference: 15°46'20"S, 15°50'37"W, altitude 790 m a.s.l.) is indented with the spring area of the Rio das Mortes which belongs to the Amazonian Araguaia-Tocantins river system (HECKMAN 1995). The geologic setting consists of tertiary sand rocks on a Precambrian basement (Cuiabá-group, GODOI FILHO 1986). Typically, the surface layers of the soils show a sequence along the height gradient of the valley which appears to be a common pattern in the Cerrado areas of Central Brazil (EITEN 1982). OLIVEIRA-FILHO et al. (1989) identified the following sequence of distinct plant communities with their respective soil types: The uppermost zone of the interfluvial Cerrado is characterized by well-drained, reddish sandy soils (latosols, UNESCO-term: ferralsols, or sandy arenosols; COUTO 1990) and Cerrado *sensu strictu* tree and shrub species and which are now largely used as cropland. These interfluves are followed by an intermediate zone with yellowish to greyish sandy soils stocked with low shrubs which passes into a marshy campo on seasonally waterlogged, black soils with grassy vegetation and - sometimes - the palm tree *Mauritia flexuosa,* and lastly the gallery forests and/or swamp forest composed by flood-resistant trees at the margins of the streams.

Habitat classification

For the classification of the habitats, the Fluvial Hydrosystem Concept (PETTS & AMOROS 1996) was applied as a classification tool for lotic systems. The nested hierarchy of subsystems comprises distinct levels: 1) the drainage basin as a landscape unit; 2) functional sectors; 3) functional sets; 4) functional units; and 5) mesohabitats. As the streams described here are only of first to third order, they are situated in one drainage basin and functional sector. *Functional sets* comprise typical ecological units associated with specific landforms, such as boulder or gravel channels, meander reaches, braided channels, and the main channel itself. A set of typical biota characterizes the habitat conditions of each *functional unit*. The individual functional units are usually arranged in spatial successions along topographical gradients which are defined, for example, by water depth or frequency and duration of inundation or drought (PETTS & AMOROS 1996). A functional unit is composed by a group of specific *mesohabitats*, such as rocky beds, gravel or sand patches, scour holes, and macrophyte stands which are changed by the variation of the water and sediment discharges, generally within years, but sometimes within days.

Water quality assessment

Water quality data (temperature, pH, conductivity, oxygen, turbidity, nitrate, nitrite, ammonium, phosphate, and calcium concentration) were measured on site using hand-held WTW series 300 probes, a HACH turbidimeter, and MERCK® field kits (for precision of these methods, see HECKMAN 1994). Regular water level readings from scales and periodic recordings with a gauge meter were correlated with periodic discharge measurements (using a MiniAir speed meter and a scale) in order to calculate the discharge of the rainy season 1994/1995.

Benthic invertebrates

Benthic invertebrates were collected using Surbersampler with a mesh size of 200 µm for total fauna of selected substrate types. Leaf packs and macrophytes mats represent substrates difficult to quantify as they have very variable volumes per sample therefore the thickness of the sampled layer was limited to the upper 5 cm. Standardized artificial substrates (bricks and folded nylon gauze of 100 x 10 cm, mesh size 1 mm) for the assessment of the recolonization capacity in variably disturbed streams. Attribution of identified invertebrate taxa to functional feeding groups was based upon results from stomach analysis (WANTZEN, unpubl.) and from critical reference to MERRITT & CUMMIN (1996).

Results

Rainfall and discharge patterns

The study area belongs to the seasonal savanna climate type (Awa-climate according to the KÖPPEN classification (HUPFER & KUTTLER 1998). Single rainfall events occurred in September and October 1994, however the core period of the rainy season was from November to April, with some rain in May and June. During July to August, rainfall was extremely rare and arid conditions occurred, with humidity as low as 13 %. During the core rain period, very strong rainstorms occurred which often yielded more than 50 mm in less than 2 hours. These events accounted for 28 to 78 % of the monthly rainfall. Rainstorms caused short flow peaks in the hydrology of the low-order streams (Fig. 2). In the early rainy season, single rainfall events above 3 mm had a short-term reflection in the hydrograph, however this effect leveled out during the rainy season. The rainfall areas were often very limited. Depending on the stream size, discharge increased 10-30 fold in small streams (base flow 5-50 l sec^{-1}), and 2-20 fold in medium sized stream (base flow 60-500 l sec^{-1}) during annually recurring rain events. The exact measurement of maximum flow was very difficult due to the irregular shape of the valley and the decelerating effect of the riparian vegetation. Subsequent rainfalls at the beginning of the rainy season caused a superposition of rising and falling hydrographs which resulted in increased average discharge (Fig. 2). During an particularly severe event in the last week of 1994, the stream valley became flooded for several successive days. Most Cerrado streams of the study area had perennial flow in spite of 2-3 months of severe drought.

In the rainy season and a period of 2-4 months after cessation of the rains, the groundwater levels of the streamside zones reached the surface level in large areas which became water-logged then. The riparian swamp-forests exchanged water with the stream in either direction, depending on local water levels. In macropores in the soft soils of these forests, this exchange was considerably fast (order of magnitude: several centimeters per second). Groundwater flow in the hillside campo wetlands towards the streams was generally slow and homogeneous (order of magnitude: several decimeters per day), however the occurrrence of rocky outcrops or more permeable aquifers sections locally caused the occurrence of circular springpools (locally called *olhos d'água*).

Naturally, Cerrado streams have crystal-clear water due to the filter effect of the campo wetlands. Local names like "Córrego Brilhante", "Rio Claro", "Rio Verde" give testemony of this original situation. During the field study, single streams differed remarkably in their sediment loads due to the variable influence of man-made erosion gullies. Only few stream sections were found to be without lateral sediment inputs. In most cases, the first erosion gully hit the stream after less than 1 km channel length and streams with an unimpaired section more than 2 km below the source were not found in the municipality of Jaciara. Often, the spring area as such was already eroded, especially in those streams that served as runoff ditch for earth roads or as drinking water supply for cattle. In heavily impacted streams, the suspensoid concentration increased dramatically with the discharge, e.g., in the Formoso stream that received inputs from an erosion gully which was several kilometers long (site FOR 5), a discharge increase from 793 to 14,500 l s^{-1} was accompanied by an increase from 60 kg d^{-1} to 783 metric tons d^{-1} (Table 1).

Physical and chemical properties of surface and groundwater

The streams of the study area revealed remarkably low ion concentrations, which were, in most cases, below detection limits. Conductivity ranged between 2.5 and 7.5 $\mu S\ cm^{-1}$ in stream water. Deep groundwater from an artesian well (approx. 100 m deep) contained 1 mg l^{-1} calcium carbonate and showed traces of chloride (<1 mg l^{-1}), magnesium (0.02 mg l^{-1}), sodium (0.1 mg l^{-1}), and potassium (0.2 mg l^{-1}). In groundwater outlets within erosion gullies, conductivities of 10-12 $\mu S\ cm^{-1}$ quickly dropped to 3-5 $\mu S\ cm^{-1}$, probably due to outgassing of carbon dioxide. In the streams of the high plain, calcium was detectable only in areas which received surface runoff from agricultural areas after lime applications. Even then, concentrations remained below 1 mg l^{-1}. Traces of nutrients were as well detectable only in agriculturally impacted areas, with low concentrations of nitrate (<0.05 mg l^{-1}), nitrite (0.03 mg l^{-1}), and ortho-phosphate (0.05 mg l^{-1}). These results corroborate the results on ion poverty in the Cerrado waters from earlier studies (FURCH & JUNK 1980; HECKMAN 1995).

Contrary to the expectations that surface runoff from limed and/or fertilized fields would considerably increase the nutrient concentrations and the algal production in the streams, neither significant changes in the water quality during and after rainstorms nor filamentous algal mats as testimonies of nutrient inputs from fertilization were detected. These occurred only in areas with direct nutrient inputs such as manure from chicken farming or below waste-water inlets.

In spite of the very flashy hydrographs of the streams (Fig. 2), the physical and chemical conditions of the stream water remained remarkably stable throughout the year (Fig 3). Oxygen concentration was near the saturation (6-8 mg l^{-1}). pH was acidic to neutral (3.3-7.2), which is typical of weakly buffered stream waters (FURCH & JUNK 1980). In the stream with the highest calcium carbonate concentration measured (Caité stream at the foothills of the Planalto, 2.3 mg $CaCO_3$ l^{-1}), the highest pH values were recorded, averaging 6.6. Conductivity increased only slightly during stormflow events. The only measured variable which showed seasonal and sporadical variation was temperature. In Southern South America, cold air masses from Antarctica influence the climate during the southern winter (June to September) and in the Planalto of Mato Grosso, air temperatures may drop from 30 to 4 °C within few hours in Mato Grosso. These cold fronts last 1 to 5 days (ALFONSI & CAMARGO 1986) and cause short-term oscillations of stream temperatures. In the rainy season which coincides with the Southern Hemisphere summer, stream temperatures also dropped due to rainfall, however to much less extent (a short rain event of 5 mm lowered the temperature about 2 °C below the minimum temperature which was registered at nights without rainfall). Small and exposed streams, such as the channels inside the erosion gullies, followed the temperature course of the air precisely (Fig. 4).

Substrate - invertebrate - relationships of Cerrado streams

The most striking feature of the Cerrado streams in the study area was that they often ran on a solid bedrock basement which was only partially covered by sediments. Thus, the occurrence of the hyporheic zone, i.e. an interstitial zone that could be colonized by the faunas of both the groundwater and the surface benthos (SCHWOERBEL 1961; WILLIAMS 1989; BRETSCHKO 1998) was limited or lacking and, consequently, potential refuges for invertebrates during storm flow events were restricted.

The mobile inorganic sediments consisted mostly of medium to coarse-grained sand. Below erosion gullies, sediment sizes were more variable, however both fine and coarse particles leveled out quickly with increasing distance to their sediment source. Due to back flooding, gravel depositions were found also above the inlets of erosion gullies.

Some substrates, such as debris dams and macrophyte packs represented densely colonized hot-spots, while scoured bedrock and mobile sandy substrates which extended over long runs generally presented very low invertebrate densities or were hardly colonized at all (Fig. 5). In SURBER samples, the following densities (ind. m^{-2}, averages ± standard deviations, n = 3) of benthic invertebrates in different substrates were found: mobile sand (19±15), scoured bedrock (33±32), sand depositions (467±440), gravel in a recovering erosion gully (2,055±1,567), bedrock with algal cover (3,004±2,786), gravel (9,788±5,272), leaf packs (21,363±13,521), floating macrophytes (111,128±23,148).

On the standardized artificial substrates, the most prominent taxonomic group was Chironomidae which represented 58 % of all invertebrate abundance, followed by Ephemeroptera (13 %), Coleoptera (8 %), Trichoptera (6 %), non-chironomid Diptera (5 %), Plecoptera and Odonata (2 % each), Heteroptera and Neuroptera (0.5 % each). Densities varied between ca 100 and ca 300 individuals per substrate set and became clearly reduced (all taxa) in sites which were disturbed by the inflow of eroded sediments from erosion gullies. Sampling before and after a rain event led to a reduction of 15-26 % of benthic fauna in reference sites and to 44-100 % in impacted sites below the gully. The most sensitive taxa at the impact sites were Plecoptera (75-100 %), Trichoptera (69-100 %), Ephemeroptera (42-71 %) and Chironomidae (36-89 %), however numbers of individual taxa were already lower before the rain event due to permanent scouring by sand inputs during baseflow (Fig. 6; (WANTZEN 1998).

Riparian forest types

Depending on the waterloggedness of the soils, different types of riparian forests develop in the Cerrado valleys. In well-drained areas, organic layers remain shallow, and streams incise mostly the clayish soils which are covered by gallery forests (locally called *mata ciliar*) which are distinct from the neighboring dryland forest or campo vegetation (RIBEIRO & WALTER 1998; RODRIGUES & LEITÃO-FILHO 2000). In wider, shallower and moister valleys, organic matter accumulates in layers up to 1 m thick on top of impermeable bedrock (WANTZEN, unpubl.). These soils develop in swamp forests (locally called *mata de brejo*) which gradually change into other forest types (BARROS 1998; VASCONCELOS 1998). These soil-vegetation-relationships have important consequences for the habitat structure of Cerrado streams in forested areas.

Habitat characterization

The depth and type of the soil layer define the occurrence of different functional sets which often alternate with each other. According to the Fluvial Hydrosystem Concept (PETTS & AMOROS 1996) the following functional sets and their subunits in Cerrado streams were identified (Fig. 7).

Functional set: Solid sandstone bedrock stretch

Functional unit: Rock channel run

This functional unit occurs with different channel plan forms. The deeply incised ones are fast-flowing (currents of 80-180 cm s^{-1}), often with small circular potholes of 30-80 cm on the stony bottom which temporarily store sediments which remain in a circular movement and is mostly devoid of invertebrate colonization. Broad rock channel stretches tend to have a higher hydraulic diversity due to the flow deviation by protruding rocks or macrophyte mats which act like little islands. Both types are often sun-exposed, as the shallow, water-logged soils near the stream do not permit the development of woody vegetation, however single specimen of shrubs (often Melastomataceae, e.g., *Tococa* sp.) occur. Adult damselflies (*Mnesarete fuscibasis*) use the shrubs as raised hides from which they attack their prey or defend of their territories. They oviposit on submerged macrophytes in slow-flowing patches of the stream. The moisture-resistant palm tree *Mauritia flexuosa* forms open stands in the hillside campo wetlands which border the stream (locally called *veredas*) and palms are often found as the only woody species occurring at the stream margin. Their lignified and slowly decomposing leaves represent important substrata for benthic invertebrates, as they retain organic matter. When streams start braidening due to erosion impacts, *Mauritia* roots and logs are the only colonizable microhabitat.
In sun-exposed, unimpaired stretches, floating macrophytes (e.g., *Eleocharis* sp.) locally provide attachment sites for invertebrates, especially filter feeders (hydropsychid caddis flies, chironomids and simulids) and rarely predators (*Limnocoris* water bugs, *Mnesarete* damselfly larvae and *Anacroneuria* stonefly larvae). In the forested rock-channels, riparian vegetation consists of swamp forest which is highly dynamic due to the limited age of the trees (WANTZEN, NUNES DA CUNHA & MONTEIRO unpubl.). Therefore, large woody debris is the prevailing organic substrate. Due to the deeper soils, the channel is generally limited by rock on the bottom and by incised forest soil of different genesis in the mostly vertical margins. This functional set is treated below.

Functional unit: Hygropetric zone

In the bedrock channel stretches, lateral water inputs are restricted to groundwater seepage from the bordering campo wetlands or from the swamp forest. Both wetland types represent sources of dissolved organic matter for Cerrado streams. At the sun-exposed sites, the rocky stream banks which are permanently overflown by a thin layer of seepage water are densely overgrown with filamentous algae which harbor chironomids and other dipterans. Higher plants (small, blade-leaved Xyridaceae and *Utricularia pusilla*) occur in small, water-filled rock pits. After stormflow events, various aquatic invertebrates, including the water bug *Limnocoris* sp. were observed in the permanently moist zone however it is unclear if the bugs migrate into the zone as a refuge or as a foraging ground. In the periodically moist zones, sand-enforced tubes from dryness-adapted insects were found, e.g., tube-building Limoniidae and Chironomidae. Compared with other hygropetric habitats, the community is relatively species-poor, typical dipteran families such as Thaumaleidae and Dixidae were not registered during a survey (WAGNER, pers. comm.). Hygropetric zones and moist stream banks are important transition corridors between the stream and the wetland (WANTZEN & JUNK 2000). Using pitfall traps open to only one side, it could be shown that similar proportions of animals migrating into one direction either from, towards, and parallel to the stream (upstream or downstream, WANTZEN & ROSA unpubl.). The most frequent taxa in these zones were Collembola (56 %), Diptera (23 %), Coleoptera (8 %), ants (4 %), and spiders (4 %).

Functional unit: Waterfalls and rapids

In the sun-exposed sections above waterfalls, dense packs of the rigid and partially emergent macrophytes (e.g., Podostemaceae , *Eleocharis* and Xyridaceae) develop a sponge-like structure which acts as a filter for fine particles and provides habitat for dense colonization by invertebrates, especially net-spinning caddis-flies (*Leptonema* sp., 600±740 ind. m^{-2}), predatory stoneflies (*Anacroneuria* sp., 4,000±240 ind. m^{-2}), and large amounts of chironomids and oligochaetes (see Fig. 5). However, all these densely colonized patches have a very limited size, while large areas of the stream channel are only sparsely colonized. The invertebrate community of bare rock areas of waterfalls and rapids is restricted to organisms with special attachment mechanisms, such as simulid larvae, and larvae of the pyralid butterfly *Petrophila* (*Parargyractis*) sp. which construct silken retreats under which they live (TUSKES 1977). In the Cerrado streams, *Petrophila* larvae withstood currents of more than 200 cm sec^{-1} and even occurred on paddle-wheels in the stream. At less fast currents (70-120 cm sec^{-1}), they co-occurred with *Leptonema* larvae which constructed D-shaped nets on the rock surface in densities up to 800±220 ind. m^{-2}.

Even in the vertical walls of the waterfalls, some areas remain with low or lacking current (dripping zone). The area behind the water curtain of larger waterfalls of the Cerrado streams is a breeding habitat for specialised birds (swifts, Apodidae). Sun-exposed rocks covered by thin water films allow the development of filamentous algae even at extremely low nutrient contents of the water. These algal mats are densely colonized by dipteran larvae.

Pools below waterfalls represent a lenitic habitat of Cerrado streams which accumulate fine particles and leaves which have much longer residual times than in the stream channel. The sandy margins and are often covered by thin organic layers. In this habitat, gomphid dragonfly larvae (*Progomphus* sp.) scavenge for chironomids, oligochaetes and nematodes. In shallow zones with low water current, baetids (*Baetis, Camelobaetidius*) were found. Various macrophytes grow in the slow flowing areas. They are much less densely colonized as those in the rapids. Small rivuliid fish breed and forage in these macrophyte beds (WANTZEN & MACHADO unpubl.).

Functional set: Swamp forest stretch

Functional unit: Riparian wetland

The organic soils of swamp-forested valleys are highly erodible and favor the development of parallel anabranches of the stream channel. Even subsurface channels occur, generally macropores of 20-80 cm diameter which run in the root zone of the trees. A duplication of the discharge on a stretch of only 20 m due to the input of several macropores was observed in a small swampland stream (C. Ajuricaba). Shallow anabranch channels become wetted only periodically during stormflow events and become divided into floodplain ponds or differently wet zones. The riparian wetland habitats of the swamp forest have a very high secondary production of dipterans (WANTZEN et al., unpubl.). In these habitats, terrestrial leaves and fruits become temporarily stored and processed, therefore they represent hot spots for the organic matter turnover (WANTZEN & JUNK 2000). Thus, the connectivity between stream and wetland is extremely high in the swamp forest stretch.

Functional unit: Stream channel in swamp-forested stretch

The stream channels are often deeply incised into the soils and have very steep bank strips which reduce the light penetration. The root systems of the riparian vegetation fix the upper part of the margins and the chann l deeply undercuts the margins. Roots and stones protruding into the stream channel, and large woody debris represent the most stable substrates which are inhabited by the organisms with the longest life spans (single large corydalid larvae and aeshnid dragonfly larvae). Floating fine roots and vertically incised margins are sparsely colonized by chironomid larvae. The most densely colonized habitats in this functional unit are debris dams. Due to the highly dynamic turnover of swamp forest trees and permanent litter input (however with seasonal peaks), the retention of leaf litter is considerably high. *Progomphus* larvae inhabit leaf packs which are partially filled with anorganic sediments. In the outer parts of the packs, nets of hydropsychid caddis flies are abundant. Only few shredding invertebrates (e.g., *Phylloicus* caddis flies) were found. The most abundant taxonomic group in these accumulations were chironomids, however in terms of biomass, the predatory stoneflies (*Anacroneuria* sp.) and dobsonfly larvae (*Corydalus* sp.) prevailed.

Functional unit: Stream pools

Scouring, especially in sequences of alternating rocky and soft substrates, causes the development of pools much deeper than the stream width. Generally, these pools are permanently cleaned by eddy current, however periodical accumulations of leaf litter in pools up to 1m thick were observed temporarily. Contrary to Amazonian streams (HENDERSON & WALKER 1986), they were only sparsely colonized by invertebrates and fish, mostly rivulids and small characoids which were observed to pick invertebrates from the vertical clay banks.

Functional set: Gallery forest stretch

In areas with better drainage of the soils, wetlands were lacking and the indentation of the stream channel with the riparian zone was less pronounced. Apart from this, the functional units and mesohabitats inside the channel were basically the same, however the riparian vegetation and, consequently, type of allochthonous organic matter inputs was different from the functional sets mentioned before. Stream stretches of this type frequently have deeply incised margins and the bottom erosion of the channel is only limited by the bedrock basement. Peak flooding has shorter and less intensive effects on the riparian zone as in the swamp forest stretches.

In few cases, natural gravel and stone sediments were found in this functional set of Cerrado streams. These had much higher abundances of benthic invertebrates than the prevailing sand or bedrock substrates. In these gravelly areas, functional units such as riffle, pool, and the hyporheic interstitial zone were observed.

Discussion

Cerrado streams represent a type of Neotropical streams which is distinct from other stream types, such as the Amazonian blackwater streams (WALKER 1995), the intermittent streams from the semiarid Northeastern region of Brazil (MALTCHIK & SILVA-FILHO 2000) or the Mata Atlântica streams (VIEIRA & EICHBAUM ESTEVES 2002). Running water ecosystems reflect the geochemistry of their catchments (SIOLI 1950, 1975). SIOLI coined the term of the "clear water" for rivers draining areas with little or no erosion and the water of which has a small to intermediate concentration of nutrients. FITTKAU (1971) distinguished between the ion-poor streams of the Guiana and Brazil shields and of Central Amazonia. He termed those streams "rainwater" streams as they have as little as or less dissolved nutrients than rainwater (FURCH 1984). In the case of the Cerrado streams of the Parecis formation, the catchments are extremely impoverished in terms of geochemistry and the conductivity of about 3 $\mu S\ cm^{-1}$ is far below that of rain water. This phenomenon has been reported by various authors (GREEN 1970; FURCH & JUNK 1980; HECKMANN 1995). The term "Cerrado stream" has been introduced for streams of Northeastern São Paulo (OLIVEIRA 1996) and Southeastern Brazil (OLIVEIRA & FROEHLICH 1997b) however without defining the term.

This paper suggests the following definition: "Cerrado streams" are characterized (a) by their occurrence on the high plains of the Central Brazilian shield within the Cerrado biome, (b) by extremely low ion concentrations and consequently weakly buffered pH values resulting from the ion poverty of the soils, and (c) by seasonally recurring flashy hydrographs during the rainy season and periods of low and undisturbed flow during the dry season.

Apart from these physical and chemical features, the biota of Cerrado streams reveal a range of characteristics which makes them interesting objects for testing of stream concepts. The presence or absence of sufficient concentrations of calcium exerts a control over the occurrence of freshwater shrimps (Palaemonidae) and molluscs, at two different threshold concentrations. Biodiversity and abundance of benthic invertebrates varied about tenfold from the Cerrado streams of the Planalto and the Piedmond streams in the transition between the foothills and the Pantanal wetland. Therefore, calcium-rich streams of the "carboniferous strips" (SIOLI 1968), e.g., in the region of Poxoreo and Cáceres, and Piedmont streams such as the Caité-Stream are considered as stream types distinct from the Cerrado streams.

In the Cerrado streams studied here, only few shredding invertebrates, considering abundance, diversity and biomass were found. Few leaves showed feeding marks of shredders and leaf litter decomposition rates were generally low (WANTZEN, unpubl.). On the other hand, the number and biomass of predatory insects was very high, e.g., dobsonfly and stonefly larvae (*Anacroneuria*). These observations led to the hypothesis that allochthonous matter other than leaves, e.g., fruit, flowers and feces of herbivorous insects from the canopy might be important food items for the stream biota (WANTZEN & JUNK 2000) while leaf litter decomposition became reduced due to the chemical composition of the leaves (STOUT 1989; WANTZEN et al. 2002). Rareness of shredders in tropical streams has been reported from many places of the World (e.g., DUDGEON & WU 1999; DOBSON et al. 2002). Thus, the trophic structure and the organic matter budgets of Cerrado streams (and potentially other Southern stream types (WINTERBOURN et al. 1981; MELO & FROEHLICH 2001) do not fit into the predictions of the River Continuum Concept (VANNOTE et al. 1980) and require the development of new approaches.

Another characteristic of Cerrado streams is the high resistance and resilience of benthic invertebrates to strong hydrological variation. Before and after spates, low differences in invertebrate abundance in pristine sites of the streams were registered (WANTZEN 1998). This result was corroborated by findings of (RAMIREZ & PRINGLE 1998; MELO & FROEHLICH 2001), however it contrasts with results from (FLECKER & FEIFAREK 1994; KIKUCHI & UIEDA 1998). Habitat stability and predictability of the period when spates occur seem to be the crucial parameters for the resistance of the invertebrates. The species traits of the aquatic insects reveals various adaptations to this type of disturbance, such as short life cycles, small body size (WANTZEN, unpubl.) and synchronous occurrence of different larval stages (OLIVEIRA & FROEHLICH 1997a).

However, coincidence of hydraulic stress with the occurrence of high sediment loads drastically reduced the benthic invertebrates and periphyton on standardized artificial substrates (WANTZEN 1998). If input of eroded material occurs in the upstream section, the stream bottom becomes covered with highly mobile inorganic sediments which remain nearly uncolonized for a long period even if the stream has a "healthy" appearance due to the (still) unimpaired riparian vegetation. Therefore, conservation programs for the whole stream valley and recovery strategies for erosion gullies are urgently needed.

Acknowledgments

This work resulted from the cooperation between the Max-Planck-Institut für Limnologie, Plön and the Universidade Federal de Mato Grosso in Cuiabá under the Governmental Agreement on Technological Development between Germany and Brazil as part of the SHIFT program (Studies of Human Impact on Forests and Floodplains in the Tropics), financed by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF), the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and the Instituto Brasileiro de Meio Ambiente e Recursos Naturais Renováveis (IBAMA). Special thanks to my students Aecio Moraes da Paula, Claudio de Oliveira Neves and Jackeline Ogawa for help with the field work and to Prof. Dr. Rüdiger Wagner, MPIL Schlitz, for helpful comments on the manuscript, and Dr. Danielle Waldhoff for improvement of the Portuguese abstract.

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Table 1: Concentration of suspended solids , discharge and suspended sediment load of four stream sites in the Cerrado region of Mato Grosso, near the city of Jaciara (avg = averages, sd = standard deviation, min = minimum, max. = maximum values, n = number of measurements including base flow, slight and strong rainstorm events).

site	**solids (mg l^{-1})**				**discharge (l s^{-1})**				**load (metric ton d^{-1})**				
	avg.	**std.**	**min.**	**max.**	**avg.**	**std.**	**min.**	**max.**	**avg.**	**std.**	**min.**	**max.**	**n**
FOR 5	71.9	143.2	4	627	1808.2	2715.3	793	14500	39.83	145.20	0.06	783.23	37
FEL 1	6.8	3.9	3	250	12.4	34.2	4	270	0.017	0.16	0.01	5.31	31
AJU 1	5.7	3.9	2	27	38.0	2.4	36	300	0.023	0.02	0.01	0.72	29
CAI 1	14.0	10.8	2	31	534.2	214.4	190	840	0.658	0.616	0.16	2.14	10

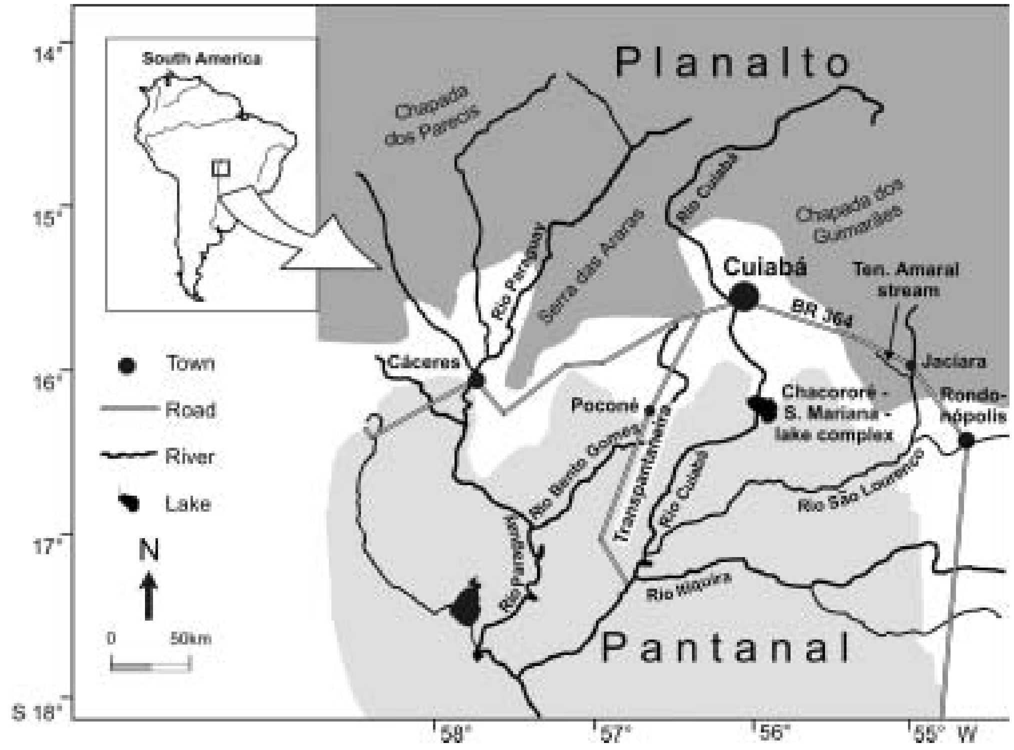

Fig. 1a:
Site map. Position of the research site within Brazil (insert) and in the catchment area of the Paraguay River, including the high plains (Planalto, dark shaded) and the Pantanal wetland (light shaded).

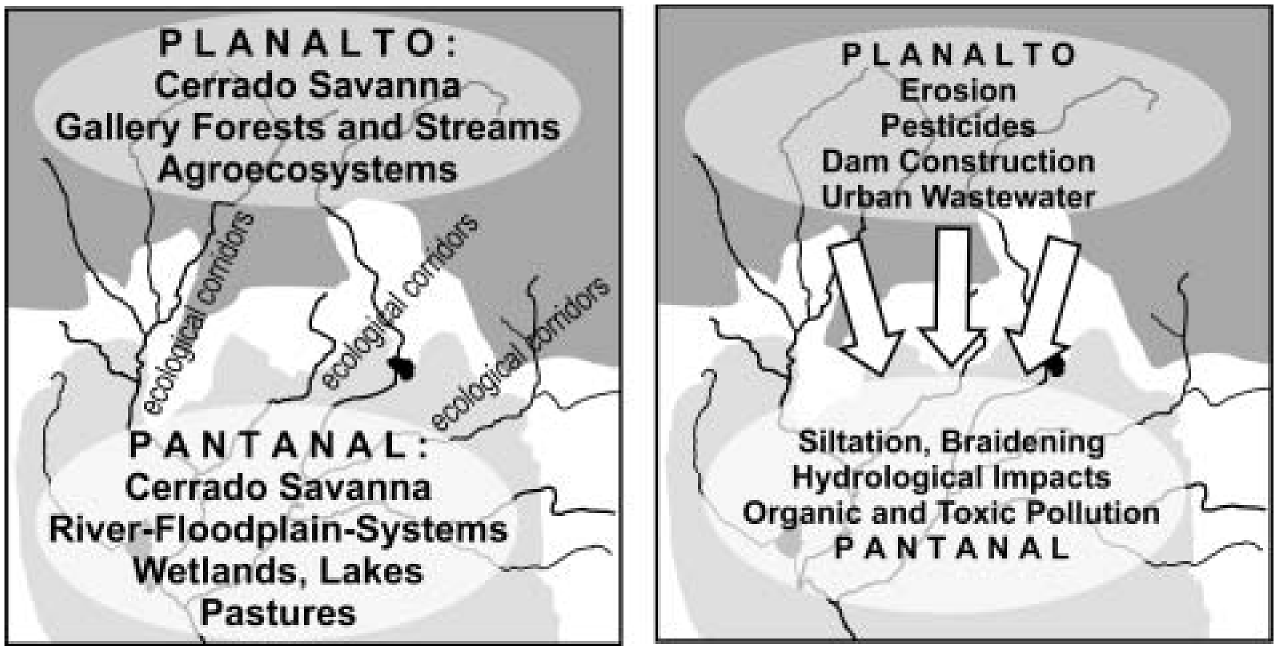

Fig. 1b, c:
Site map. **b** (left): Importance of the tributary systems to the Pantanal as corridors for the connectivity of populations of the Pantanal and the Planalto. **c** (right): Importance of the Planalto for the export of pollution from the catchment area into the Pantanal wetland.

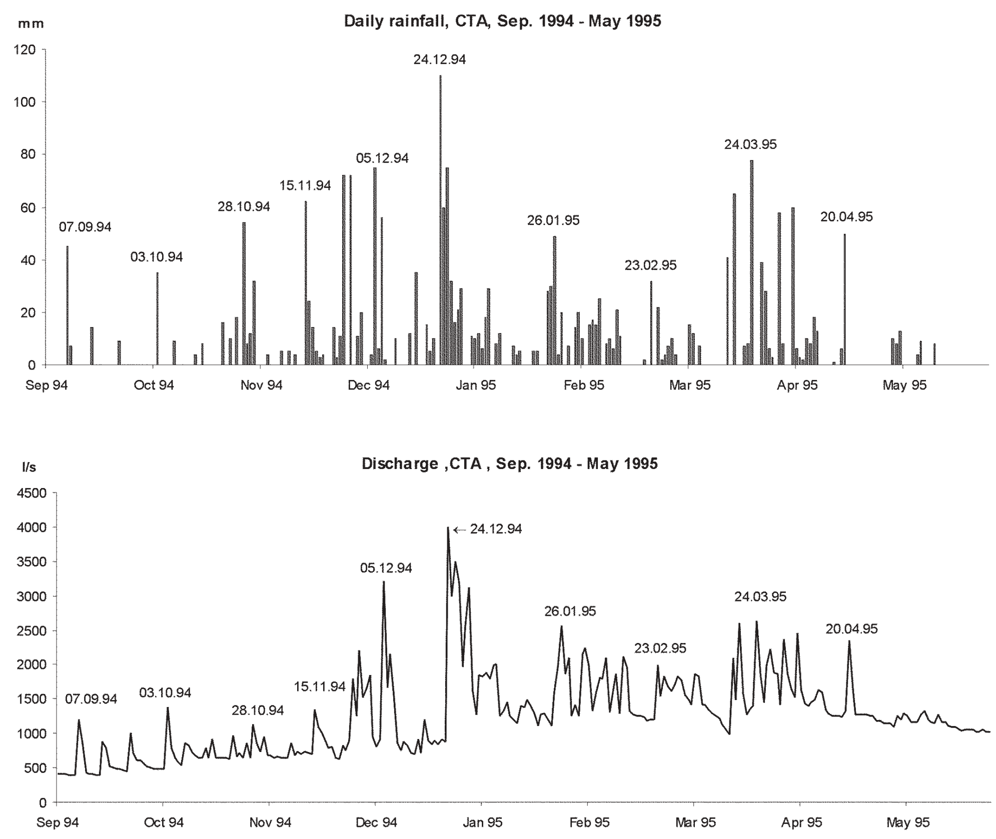

Fig. 2:
Daily rainfall sums (above) and discharge (below) at the Tenente Amaral stream during the rainy season 1994-1995. Note the heavy rainfall events in the last week of 1994 which yielded 343 mm or 14.2 % of the annual precipitation.

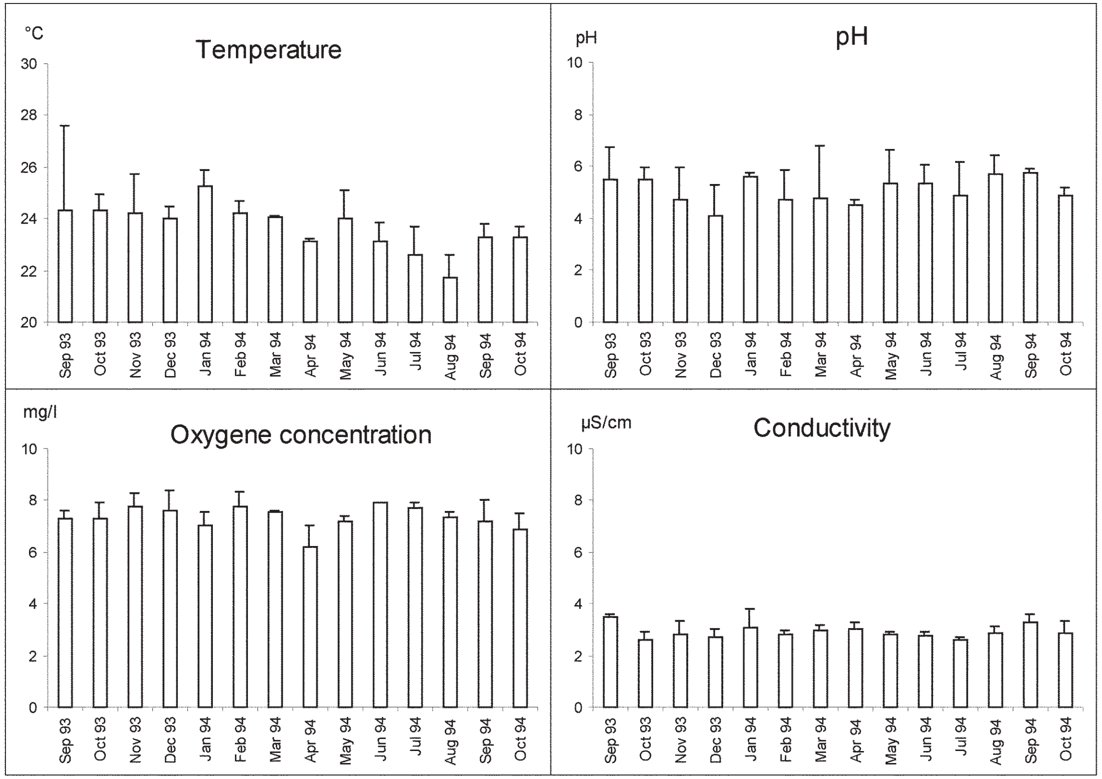

Fig. 3:
Annual pattern of temperature, oxygen concentration, pH, and conductivity of a Cerrado stream of Mato Grosso (Córrego Félipe); means ± standard deviation (n = 35).

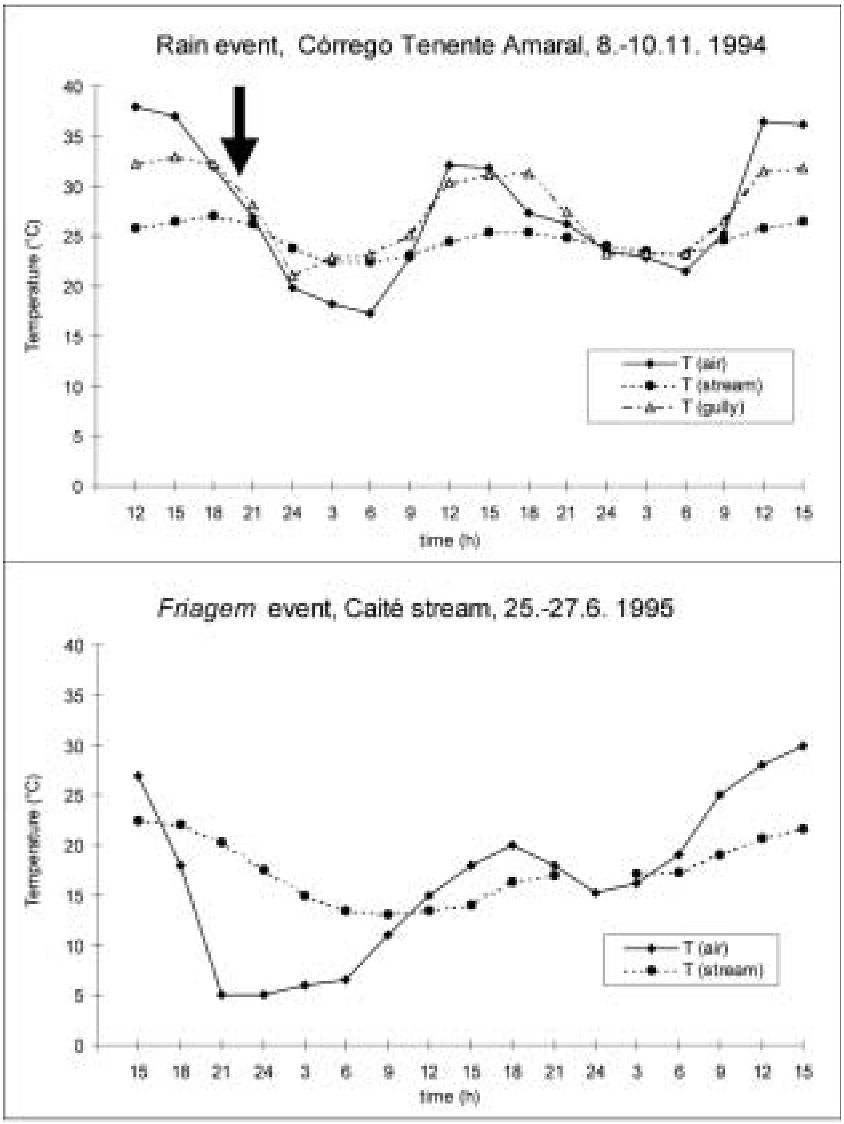

Fig. 4:
Rapid changes in air and stream water temperature. Above: temperatures of the Tenente Amaral Stream and a small erosion gully flowing into it. Changes were caused by a 5 mm rain event wich lasted 30 minutes (arrow). Below: temperatures of the Caité stream during a cold front event (locally called *friagem*).

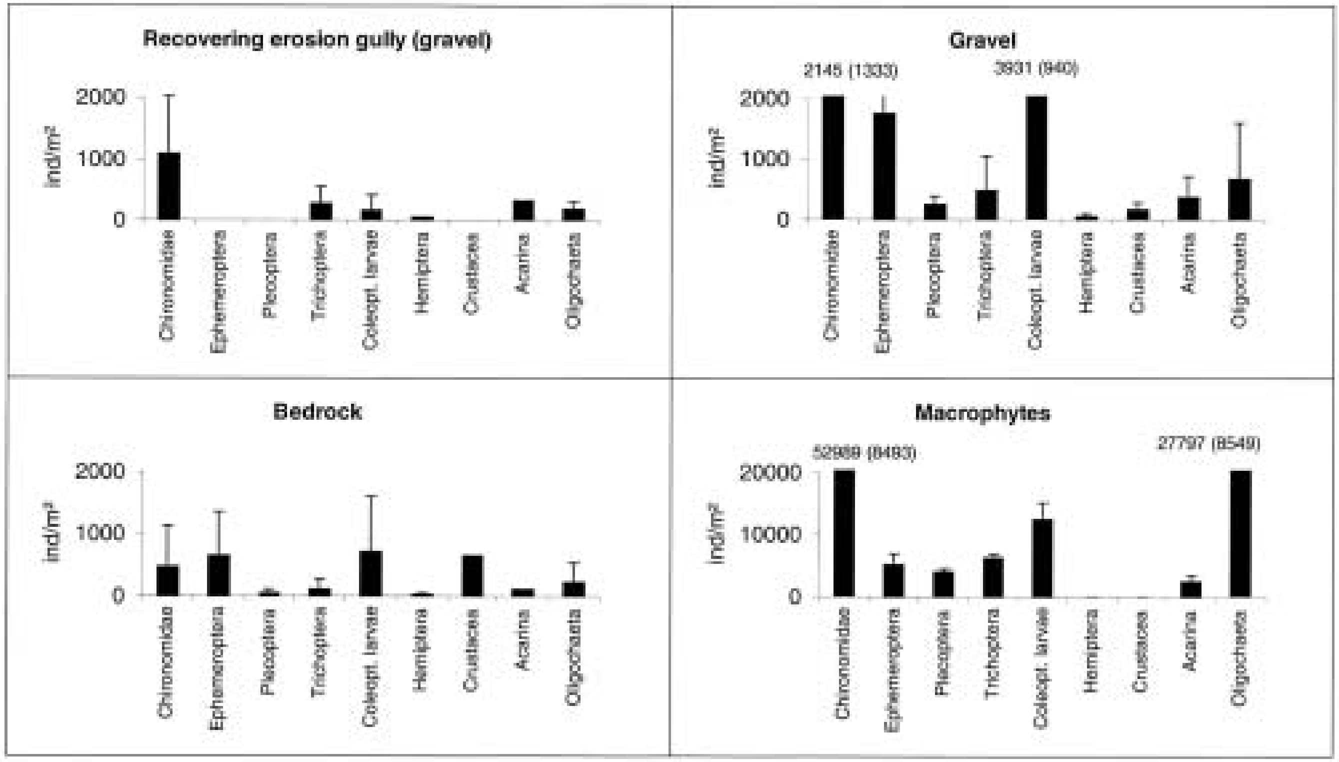

Fig. 5:
Benthic invertebrate densities (ind. m^{-2}) of different substrates of the Tenente Amaral stream. Average values and standard deviations of three replicate SURBER samples taken during the rainy season (January 2001). Please note that the scale in "Macrophytes" is tenfold the scale in the other graphs. Figures in the graph indicate values exceeding the scale.

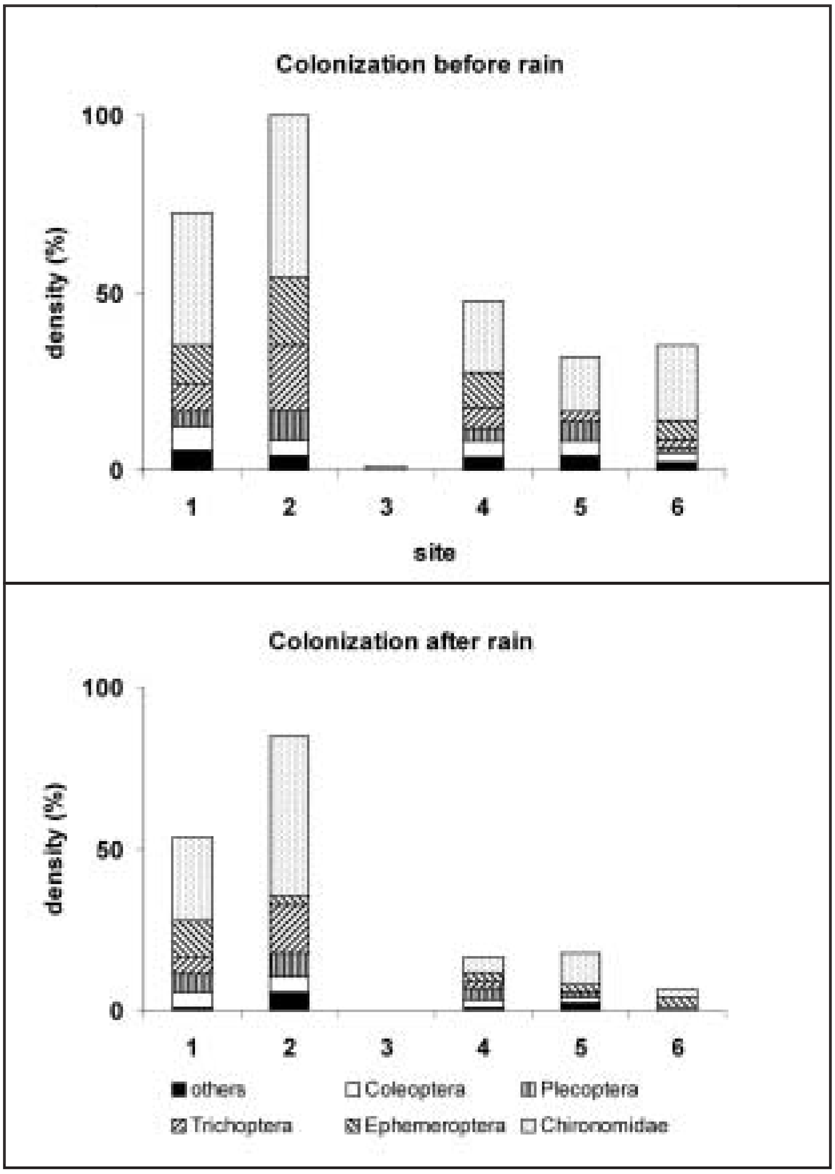

Fig. 6:
Impacts of a single rain event (48.5 mm) on benthic invertebrates on standardized artificial substrates. Maximum density (214 ind./substrate) was set to 100 % for clarity of scale. Relative density before the rain event (above) and after it (below). Site numbers 1-6 refer to forested reference site (**1**), sunny reference site (**2**), mouth of erosion gully (**3**), sites 10, 100, and 1,000 m below the gully (4-6). Data from (WANTZEN 1998).

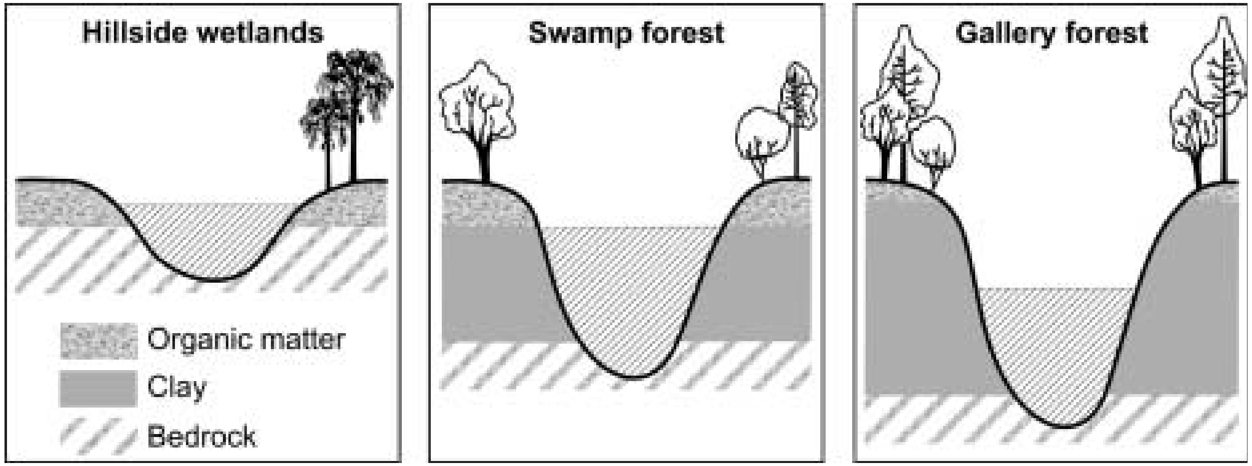

Fig. 7:
Stream-riparian-zone systems of Cerrado streams in Mato Grosso. Left: In areas with shallow, permanently water-logged organic soils on bedrock, the riparian zone is characterized by hillside wetlands (*campos úmidos*) which may be interspersed with *Mauritia* sp. palms (*veredas*). Middle: Deeper, almost permanently waterlogged soils (clay covered by organic matter) are covered by swamp forests which often have secondary channels and temporary pools. Right: Gallery forests which are distinct from the surrounding Cerrado *s.str.* vegetation occur on drier and deeper soils with shallower organic matter layers.