Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **31**, 81–96 (2006)
DOI: 10.1002/esp.1235

Effect of dyke construction on water dynamics in the flooding savannahs of Venezuela

J. K. Smith,[1]† E. J. Chacón-Moreno,[2] R. H. G. Jongman,[1]* Ph. Wenting[1] and J. H. Loedeman[1]
[1] *Department of Environmental Sciences, Wageningen University, The Netherlands*
[2] *Universidad de los Andes, Instituto de Ciencias Ambientales y Ecológicas (ICAE), Mérida Venezuela*

**Correspondence to:*
R. H. G. Jongman, Alterra
Green World Research,
Wageningen UR, PO Box 47,
6700 AA Wageningen,
The Netherlands.
E-mail: rob.jongman@wur.nl

†Present address: Universidad de los Andes, Instituto de Ciencias Ambientales y Ecológicas (ICAE), Mérida, Venezuela

Received 11 February 2004;
Revised 3 January 2005;
Accepted 5 February 2005

Abstract

In the flooded savannahs water is the main factor determining the ecosystem and its change. During flooding, the level of water and the duration of flooding are highly dependent on the relative height position of the ecosystem unit. To understand the spatial processes in the ecosystem one must know the water dynamics in the area. In order to quantify the water content during the year, a digital elevation model (DEM) is needed.

Several areas in the Llanos de Orinoco have been dyked (modulos). A digital elevation model has been developed on a level of the dyked area of the modulo of Hato el Frio. Flooding has been studied at the regional level and a DEM has been developed for the modulo area. For the construction of the DEM various sources were explored for height information. Field measurements with GPS were necessary.

After the high flooding period downstream of the dykes the area is totally dry. In the transition period between the dry and the wet season the distribution of water shows a clear influence of the dyke. In the natural situation the natural height differences create a complex system of sinks. The dyke construction has created a large artificial sink. Modulos form sinks by their banks preventing the outflow of the water. With the help of a DEM, inundation can be modelled with relatively little field research.

Keywords: digital elevation model; flooding regime; Orinoco; river floodplain; wetland; savannah

Introduction

The flooded savannahs of central Venezuela or the Llanos of Apure, occupy an important extension, approximately 30 000 km^2, of the Llanos of Venezuela (Sarmiento and Pinillos, 2001). In the flat landscapes of this region the annual dynamics of flooding is the key ecological factor controlling ecosystem structure and functioning, as well as cattle breeding, which is the main human activity in the region. Cattle stocking rate and spatial distribution over the year depend on the inundation of the area. The cattle feed on natural pastures and the available fodder over the year is very variable. In the Llanos de Apure the bottleneck for cattle breeding is the dry season, when only the lowest part (esteros) continues to produce grass and in the other areas grass is dry and often submitted to burning. In order to overcome this shortage during the dry season, dykes and small polders or 'modulos' were built for water storage. This measure had its beginnings in the 1960s and state programmes, known as the 'Modulos de Apure', were implemented in the 1970s. With the building of modulos the stocking rate could increase from 0·2–0·25 to 0·6–0·75 animal-unit/ha (Betancourt *et al*., 2001). The dykes have various models, some have floodgates and others are simply earth walls that are broken with excavators when necessary. The dykes are usually placed diagonally between two riverbanks and each modulo can be considered as a separate hydrological unit. Careful planning of the dyke location is crucial, as it can also lead to the undesired inundation of areas important for cattle grazing during the rainy season (Schargel and Gonzalez, 1972).

Inundation is the principal factor determining the ecological functioning and land use of these savannahs; however, detailed knowledge of the precise relationships between relief and inundation patterns and the effects of the dykes is scarce (Sarmiento and Pinillos, 2001). Therefore the first objective of this study was to develop a methodology to

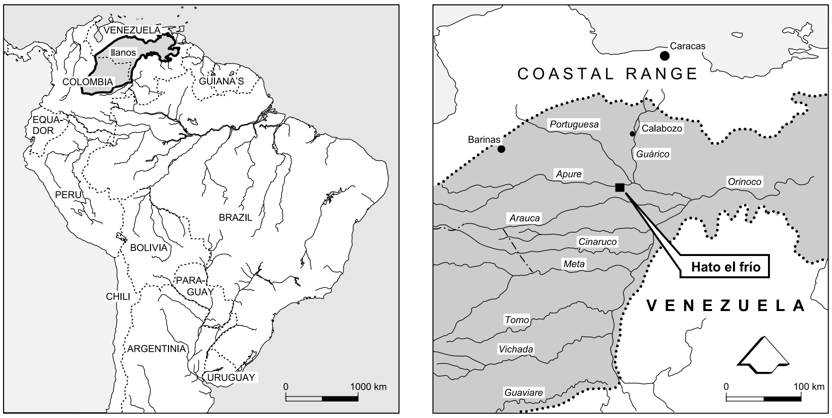


Figure 1. Location of the Hato el Frio in the Llanos de Orinoco. The grey area is the Llanos de Orinoco, the lowlands of the Orinoco River.

construct a digital elevation model (DEM) for a very flat area, where available topographical data are very limited and of poor quality, but at the same time relatively high precision is required because small differences in altitude can have a large influence on the water dynamics. The second objective was to use this DEM, in combination with fieldwork data and classified radar images, to analyse the flooding dynamics of a modulo as the unit of water management in the area. A third objective was to evaluate the effect of the dyke on the water volume by comparing the current situation with the state before the dyke was built using a hydrological model. Finally, the topography of the modulo has been related to the different geological epochs in order to discuss whether geological maps can be used for generalization of the results of this study to neighbouring areas, as height information for these flat ecosystems of Venezuela is not available at the quality or vertical precision needed for more detailed studies.

The study area is situated in the Hato El Frío, an 80 000 ha farm in the north of Apure State (Figure 1). The rivers Apure and Arauca flow from west to east. In order to manage water, dykes were built in 1960, surrounding and dividing an area of approximately 5700 ha. A central dyke, crossing the floodplain in a north–south direction, divides the area into an upstream and downstream part and has changed the hydrological dynamics of the area. Gallery forest is found along the banks of the main stream and, depending on the relative height of the terrain, seasonal, hyperseasonal and semiseasonal savannah occupies the rest of the area.

Environmental Conditions

Geomorphology and ecology

The middle Apure savannahs can be divided on the presence of a flooding period and its duration into three main types of savannah ecosystems: seasonal, hyperseasonal and semiseasonal (Sarmiento, 1983). The semiseasonal savannah (locally named estero) is an ecosystem in which the water excess period lasts almost the entire year and water shortage either never occurs or is very brief. The hyperseasonal savannah or bajío is defined as having four contrasting seasons. In the dry season the soil is totally dry and in the wet season it is flooded. Consequently the ecosystem passes through two periods of contrasting stress (flooding and drought) and two transitional periods between them. The seasonal savannah or banco is the highest part of the savannah and is only affected by the dry season, as it is not flooded during the wet season (Figure 2). The occurrence of these savannah types, their proportion and spatial distribution are very important for the biodiversity as they represent different kind of habitats and offer resources for the fauna in different periods of the year (Tamisier and Dehorter, 2000; Rivas *et al.*, 2002).

The study area represents a characteristic subsidence area of the Colombian-Venezuelan Llanos. The hydrological dynamics of the area are largely determined by the topography, which depends on geomorphology and geology. The Llanos are formed by alluvial overflow plains and in our study area the sediments found correspond to the epochs from upper Holocene to the lower–middle Pleistocene. The older sediments are deposited over a wider area than the younger ones. The Pleistocene sediments (Q3) are deposited over almost the entire area and are covered by middle Holocene sediments (Q1 and Q2) in a discontinuous form. The younger Holocene sedimentation (Q1–Q0) conserves

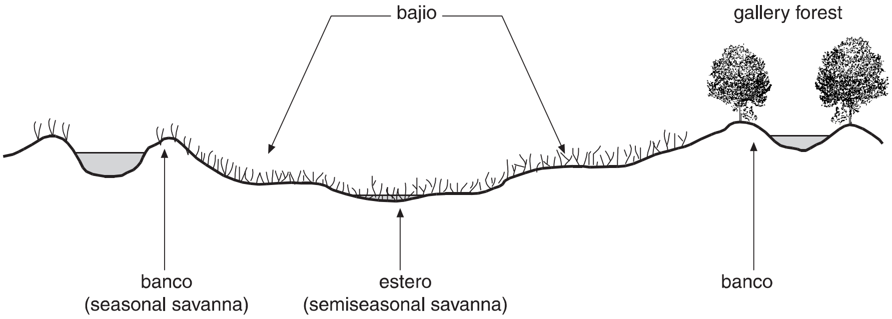


Figure 2. Floodplain units and their related vegetation before dyke construction (side view). The units are banco (bank) or seasonal savannah, bajío (flats) or hyperseasonal savannah and estero (basin) or semiseasonal savannah.

its original forms, produced by the fluvial dynamics (natural levees or banks, flat overflow areas and decantation basins) (ECOSA, 1980; Vivas, 1992; Sarmiento and Pinillos, 2001). Although the relief is a fundamental factor for flooding dynamics, the altitudinal differences are very small and tiny variations can have an important effect; consequently the analysis of the water dynamics requires precise knowledge of the relief. The banks are formed by coarser sediments (sands), in the flat overflow areas silt sediments were deposited (bajío) and in the decantation basins fine sediments (clay) settled (estero) (Sarmiento, 1983).

Hydrology

In the Apure plains the mean annual precipitation estimated from a 26-year record shows a slight east–west gradient with a yearly rainfall of 1300 mm in San Francisco de Apure and 2760 mm in El Nula, 500 km westward, showing a sharp increase due to the Andes chains (Sarmiento and Pinillos, 2001). The nearest climatic station to the research area is in Mantecal, approximately 80 km west of the study area. The climate shows a peak of rain in June and the driest months are from December to March with an average total precipitation of 1590 mm. The monthly mean temperatures vary between 25·4 °C in July and 28·5 °C in March.

The two main water sources for the inundation in the study area are overland flow from upstream areas and precipitation. The yearly rainfall and its distribution over the year are important factors for determining the flooding dynamics. The precipitation pattern is very seasonal, with at least four to five dry months (December to April) when the potential evapotranspiration largely exceeds precipitation. In May water starts to accumulate in the area, when evapotranspiration falls below precipitation. After October evapotranspiration surpasses the rainfall and inundation begins to diminish. Therefore flooding reflects the precipitation patterns (ECOSA, 1980; Sarmiento, 1983).

Another factor that favours flooding in this area is found in the soil characteristics. Due to the strong seasonality of the climate the alfisols and ultisols form argillic horizons that are often associated with ferric concretions. These hardpans have almost no hydraulic conductivity (Sarmiento and Pinillos, 2001; Malagón and Ochoa, 1980). Therefore exchange with groundwater is absent in the area.

In the flooding savannahs water is the main factor that determines the ecosystem and its change. During flooding, the level of water and the duration of its maintenance are highly dependent on the relative height of the ecosystem unit. To be able to study the water dynamics in the area and especially to quantify the water content, a DEM is needed. As the study area is very flat (overall slope W–E < 0·5 per cent) the height information for the DEM construction has to meet a high vertical accuracy.

Methodology

General

For the construction of the DEM various sources were explored for height information. Topographical maps of the area show height information only for a limited number of points, which is not sufficient for the DEM construction. Moreover, most are not validated. The possibility of constructing the DEM from aerial photographs by using only photogrammetric methods was tested, but due to the flatness of the study area and scale of the photographs (1:50 000) the obtained results were not satisfactory. Estimation of height differences did not appear to be easily possible. As the results from interpreting topographic maps and aerial photographs were insufficient, additional field measurements with GPS became necessary. This method of data collection is very time-consuming and in order to create a DEM for the area of the modulo of the Hato El Frío (57 km^2) a combined method of GPS field measurements and aerial photograph interpretation was developed and applied.

GPS measurements

In March 1998 a three-week field campaign was carried out for terrain measurements with real time kinematic geographical positioning system (RTK GPS). In the first week a continuous 48-hour measurement was performed to counteract the selective availability (SA) distortion in these years deliberately imposed on the GPS signals by the US Department of Defence. For a single autonomous (single receiver) GPS position the SA effect was on average *c*. 100 m (2σ). By logging GPS positions on a fixed point (station) for about 48 hours with a 1-minute interval the SA effect was nearly cancelled out. The mean position expressed in the GPS reference system (WGS84) shows an absolute positional accuracy (XY) of about 5 m (2σ).

From this 'point of origin', baselines were measured to and between four points located in the modulo of the Hato El Frio and a single base line to the triangulation vertex Macanillal. The terrain description and the XY position in the local (national) UTM grid of this vertex were obtained from Cartografía Nacional de Venezuela, División de Geodesía. Two other triangulation vertices in the area could not be found, probably due to house or dyke construction.

All baseline measurements were post-processed in the WGS84 reference system resulting in an adjusted network of reference points. After a datum transformation from WGS84 to the local reference system (Ellipsoid: International 1924/Provisional South American 1956; datum point 'La Canoa') and a subsequent projection/transformation to the local UTM grid, these reference points could be used as base stations for the measuring transects. Afterwards all RTK positions were transformed to UTM XY and a relative Z (better than 15 cm accuracy).

With the RTK GPS a total of 5500 points were measured (Figure 3). These points contained transects over the entire modulo study area, profiles of selected topographical features such as dykes, riverbeds and their banks, ground control points for the georeferencing of the aerial photographs and sample points for water level measurements.

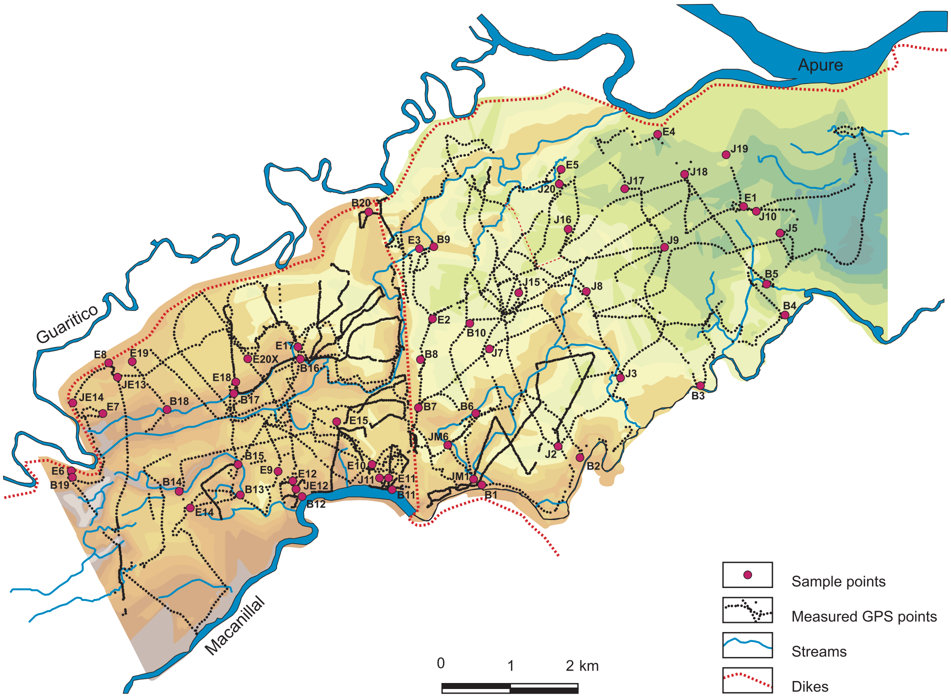


Figure 3. Digital elevation model of the Modulo Hato el Frio. Brown indicates the highest part of the area, green and blue are the lowest. Sample points (numbered) and GPS points (dotted lines) are indicated.

Table I. Normalized sample point heights

	Banco	Bajío	Estero
Average	67·60	67·31	66·95
Minimum	66·97	66·91	66·01
Maximum	68·22	68·12	67·53
Standard deviation	0·31	0·29	0·36

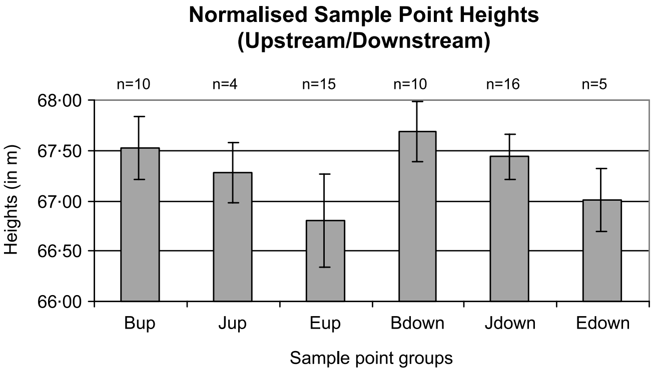


Figure 4. The heights of the normalized sample points divided into upstream and downstream. Bup, upstream bank points; Jup, upstream bajío points; Eup, upstream estero points; Bdown, downstream bank points; Jdown, downstream bajío points; Edown, downstream estero points.

DEM construction

Transects were driven with a four-wheel drive car measuring X, Y and Z every 50 m. The average distance between transects was 400 m and where accessibility was difficult due to dense bushes and trees, a larger separation of transects (maximum distance 700 m) was accepted (Figure 3). In the inundated areas driving was impossible and transects had to be measured on foot, but as the dry season was very pronounced in 1997/98 (ENSO effect) only relatively small areas were flooded at the time of the fieldwork. The profiles were located over the entire area and 85 topographical and geomorphologic units (dykes, small riverbeds and their banks) were measured. This information was collected in order to assign height values to streams, dykes and banks digitized from the aerial photograph interpretation. The data show that there is no large difference between the different sample point groups even when eliminating the general slope (Table I, Figure 4).

For the construction of the DEM, linear features such as riverbanks are important especially as they can function as barriers for superficial runoff. As these features are not always captured in their total extension, when measuring transects over an area, the information has to be obtained from a different source. In the case of the Modulo Hato El Frio, the area is too large to measure sufficient transects in an acceptable time period to be able to extract these linear features directly from field measurements. For this reason additional information was obtained from orthophotographs, obtained from the aerial photographs (1978, 1:50 000), by digitizing onscreen the main linear terrain features such as rivers and dykes. By overlaying the measured GPS points, principally the measured profiles, the width and the height of these features were determined. As not all the streams are bordered by banks, the ones that are had to be identified and selected. The average width of the banks was 35 m; this value has been used for interpretation of streams with banks on the aerial photographs. The heights of the banks were automatically assigned, using the height information from the measured profiles. The heights of the river and streambeds were also extracted and automatically allocated to the stream segments. As for the main dyke, the mean altitude was selected for the entire dyke. The actual height oscillations are of no importance, because the dyke is always so high that it acts as a barrier to superficial water.

As the measured transects were not very dense and in some areas driving was only possible along the stream banks, notes were taken in the field on all profiles and transects. With the help of the notes, problematic points could be identified and eliminated. Another problem was that individual points on banks or in riverbeds lead to an overestimation of these heights when interpolating the information, for example, if a point is measured in a riverbed leading to a depression in the DEM where no depression exists. The same applies to points on banks, which cause an elevated area in the DEM. These points have to be corrected when the DEM is calculated. These problem points are identified by calculating a provisional DEM with all the points and overlaying it with the digitized photo interpretation. These points have then to be corrected.

Using the corrected GPS points and segments a triangulated irregular network (TIN) was generated. A TIN is a three-dimensional model of a surface that defines an area as a set of contiguous, non-overlapping triangles, which vary in size and angular proportion. A height value is recorded for each triangle node and the heights between the nodes are interpolated. The advantage of using this method instead of interpolating the points to form a grid is that a TIN can accommodate irregularly distributed data sets and accepts linear as well as point data as input (Burrough and McDonnell, 1998).

The different landforms present in the study area were analysed by comparing the DEM with the geological map (Pinillos, 1999). Profiles were automatically extracted from the DEM and the geological epoch that was crossed was assigned.

Water dynamics

To study the water dynamics, second European remote sensing satellite synthetic aperture radar precision images (ERS2 SAR PRI) of the study area were acquired. The dates of the radar images were 7 May 1998, corresponding to the transition period between the dry and wet season, 20 August 1998 for the wet season, and 3 December 1998, the transition period between the wet and dry season. The image corresponding to the dry season was not recorded and therefore an ERS1 SAR image from May 1992 was used. This was possible because in 1992 the months until May were very dry and there was very little flooding. The pixel size is 12·5 m and the spatial resolution approximately 30 m. The radar images were processed and classified with ground control areas and flood maps were created for the different seasons. The flood maps for the study area have to be calculated by combining all four radar images into one synthetic image to prevent the wrong interpretation due to the thick cover of fast-growing water hyacinths (Jongman *et al*., 2005).

In order to follow the temporal water level upstream from the dyke, 10 rulers were installed along the dyke, located every 400 m at a distance of about 30 m from the dyke. The reading of the water level was needed for interpretation of the modelling results and was carried out with binoculars during the periodic field trips when the area was flooded (1997–1999). The exact position and height of the rulers was determined with the RTK GPS. Apart from the data collected with the rulers, additional water level data were collected at different locations and times of the year. Sixty fixed sample points are established throughout the area and within the types of ecosystems (Figure 3). At these locations the water depth was measured with a ruler and the position was determined with RTK GPS. Concerning the fieldwork, it was sometimes impossible to enter the study area during the wet season and programmed sampling dates could not always be met. However, that did not influence the results, because all rulers were flooded as was shown by later examination.

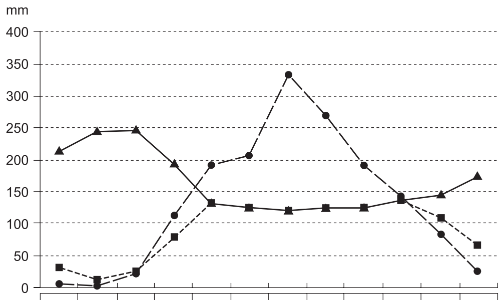
Using radar images, inundation patterns at different times of the year can be detected, but the amount of accumulated water in the area during the wet season cannot be derived. The DEM offers the opportunity to study the hydrology and quantify the collected water. It can also help to interpret the flooding dynamics of an area.

The analysis of the flooding in the Modulo Hato El Frio is divided into three parts.

1. The flood maps, obtained from the radar images (Jongman *et al*., 2005), are analysed using the DEM allowing the quantification of the accumulated water in the modulo.
2. The flooded areas and the water volume of the upstream area (from the dyke) are calculated for different periods using the DEM.
3. Hydrological simulation is used on the field data and to detect the flooding process of the sinks in the area upstream of the dyke.

For the detection of areas of internal drainage, the hydrological modelling extension of Arcview was used. Usually for hydrological modelling a DEM free of depressions is required, as small sinks in elevation data are most commonly considered to be due to errors in the data. Because of the nature of our study area, the majority of the small sinks are considered to be real. Therefore, the only application of the hydrological model extension that can effectively be used is that of filling the sinks. This process fills each depression in the DEM to the elevation of the lowest overflow, taking the flow direction of each cell into consideration, and with that the areas of potential flooding are identified. This modelling was carried out on two DEMs, one with the dyke and another without.

For the calculation of the water volume two approaches were applied. The first was to overlay the DEM with the flood maps created from the radar images and the other was to use water level heights measured in the field and model



Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
5	3	21	110	191	205	336	269	192	144	88	26	Precipitation —●– –
214	243	247	195	133	124	121	124	124	137	146	177	ETP —▲—
31	13	24	78	133	124	121	124	124	137	110	67	ETR - -■- -

Figure 5. Climatogram of Mantacal 80 km west of the study area (ECOSA, 1980).

the inundation. To calculate the volume of the water accumulated in the modulo at the dates of the radar images, the classified radar images were combined with the DEM. New grids were created, showing the DEM only for areas that were classified as flooded in the images. To estimate the water height for the different periods, the borderlines of the inundated areas of each new grid were analysed on the radar images. As the borderline of a continuously inundated area has the same height all around, the absolute water level heights can be extracted. With these water level heights and the grids showing the DEM only for the inundated areas, the volume of the water flooding the areas can be calculated. DEM height values are subtracted from the water level height, giving the water depth over each height group of cells. Combined with the area it provides the total water volume. Downstream of the dyke, the area was divided into three zones based on relative height and distance to the dyke, as the inundated areas were not continuous and there is a large difference between the areas close to the dyke and the area further downstream. In each zone, the water level was at a different height. Upstream from the dyke, one single value for the entire area defined the water level, as the inundated areas were more continuous.

Modelling the inundation was only possible for the area upstream from the dyke, as the DEM does not include the entire catchment area. Therefore there is no real downstream boundary condition to be included. The downstream boundary of the DEM acts as an artificial second dyke restraining the outflow of the water. The inundation was modelled for the upstream part of the DEM by filling the water level to heights measured in the field. In this newly constructed DEM for the upstream area the central dyke was lowered from 72·0 m to 69·89 m, which represents the height 1 cm above the highest point in the terrain.

For the volumetric analysis, the area between the TIN surface and the horizontal plane, formed by the water surface and located at a specified height, is calculated. To model the spatial extension of the flooding, different grids were created with all cells containing the water level height of the specific fieldwork dates. The two height images, the TIN and the water level grid, can be compared. Areas that lie below the water level are separated from the areas above, simulating the flooded area for a specific water level height and giving the volume of the area between the two surfaces.

Comparison of the calculated water volumes with the climatic data of the same year was not possible as these data were not available. Therefore, they were compared with an average year from the data of the climatic station of Mantecal. In the study of ECOSA (1980), the potential and real evapotranspiration is calculated (Figure 5). The potential evapotranspiration is derived from the pan evaporation and the correction factor is 0·8, a factor used for Venezuela. The real evapotranspiration is calculated with the Budyko method and the estimated retention of water in the soil for the area of Mantecal is 100 mm. To obtain the water remaining in the area, when not taking drainage into account, the real evapotranspiration was subtracted from the precipitation.

Results

The DEM for the modulo Hato el Frío

The digital elevation model of the study area is shown in Figure 6A. The main slope is in the WSW–ENE direction. Over a distance of 12·8 km the height difference between the highest and the lowest area is 3 m (66·8 m to 69·8 m).

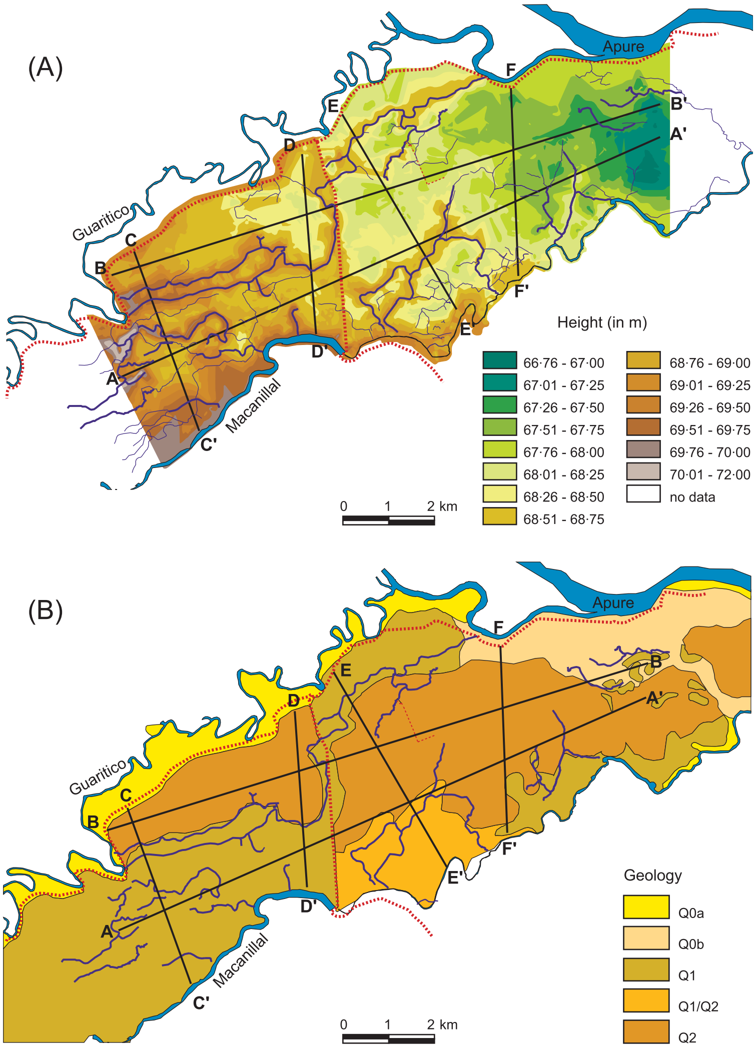


Figure 6. The position of the profiles crossing the DEM (A) and the position of the profiles on the geological map (B). Key to geological map: Q0a, upper Holocene; Q0b, lower Holocene; Q1, upper Pleistocene; Q2, middle Pleistocene; Q3, lower Pleistocene (from Pinillos, 1999).

This is equivalent to a general slope of 0·013°. Apart from the general inclination, the slopes inside the area can be derived from the TIN, resulting in a slope map. Over 65 per cent of the area has slopes below 0·1° and only 3·35 per cent has slopes over 1°. These steeper slopes are found on the dykes and some larger banks.

For visualization of the topography of the area, six profiles were extracted from the DEM. In Figure 6A the position of these profiles is given and Figure 6B shows the profile positions on the geological map. Two profiles are situated in the direction of the main slope and four transverse.

In Figure 7, it can be observed that profile A–A′ crosses several river banks. Upstream from the dyke the general slope is practically flat whereas downstream the slope is steeper. When comparing both profiles, profile B–B′ shows a relatively continuous slope over the entire area. The difference between the two profiles can be related to the age of the sediments that are crossed. Comparing the position of the two profiles, profile B–B′ lies inside Q1 over virtually the entire area, whereas A–A′ crosses Q2 upstream from the dyke. In general the higher banks are found in Q1. This can be observed more clearly in the profiles, which lie vertical to the main slope (Figure 8). The main difference between the two epochs in our area is that the older sedimentation forms have been subject to fluvial erosion for a longer period, erasing the natural levees and filling the basins.

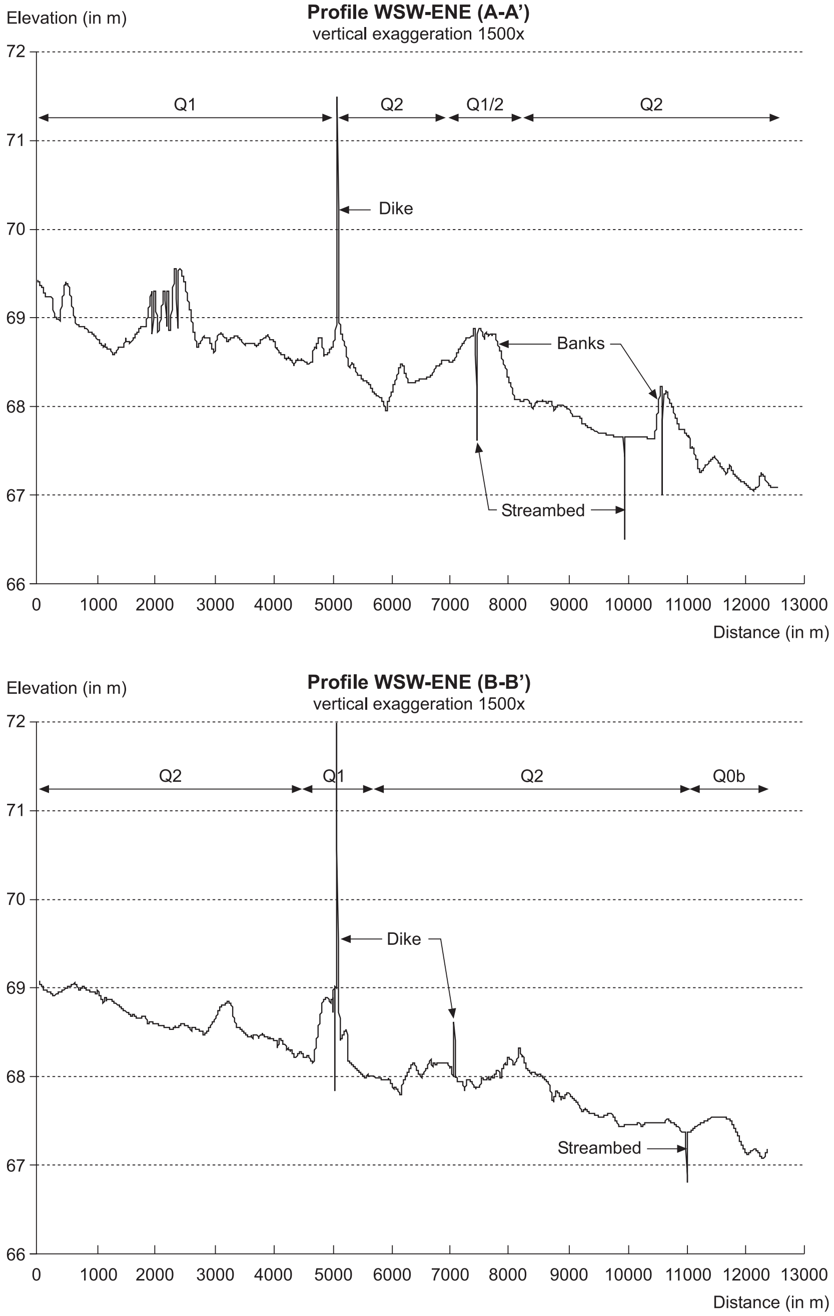


Figure 7. Profiles in direction of the main slope in the area and the epoch of the sedimentation of the area that is crossed. The profiles are at a right angle to the main dyke. For interpretation of the geological layers see Figure 6B.

The comparison between the different profiles, vertical to the main slope, shows that the terrain level of Q1 is slightly higher than Q2 as in profile D–D′ (Figure 8). In Profile C–C′ this is not the case, because the profile crosses a sink in Q1, which can also be recognized in the DEM. Profile F–F′ shows that when no banks are crossed, there is also a slope in a northerly direction. The degree of the slope is relatively high because of the influence of the bank of the Macanillal. The comparison between the DEM and the geological map shows the relationship between the age of sedimentation and the topography.

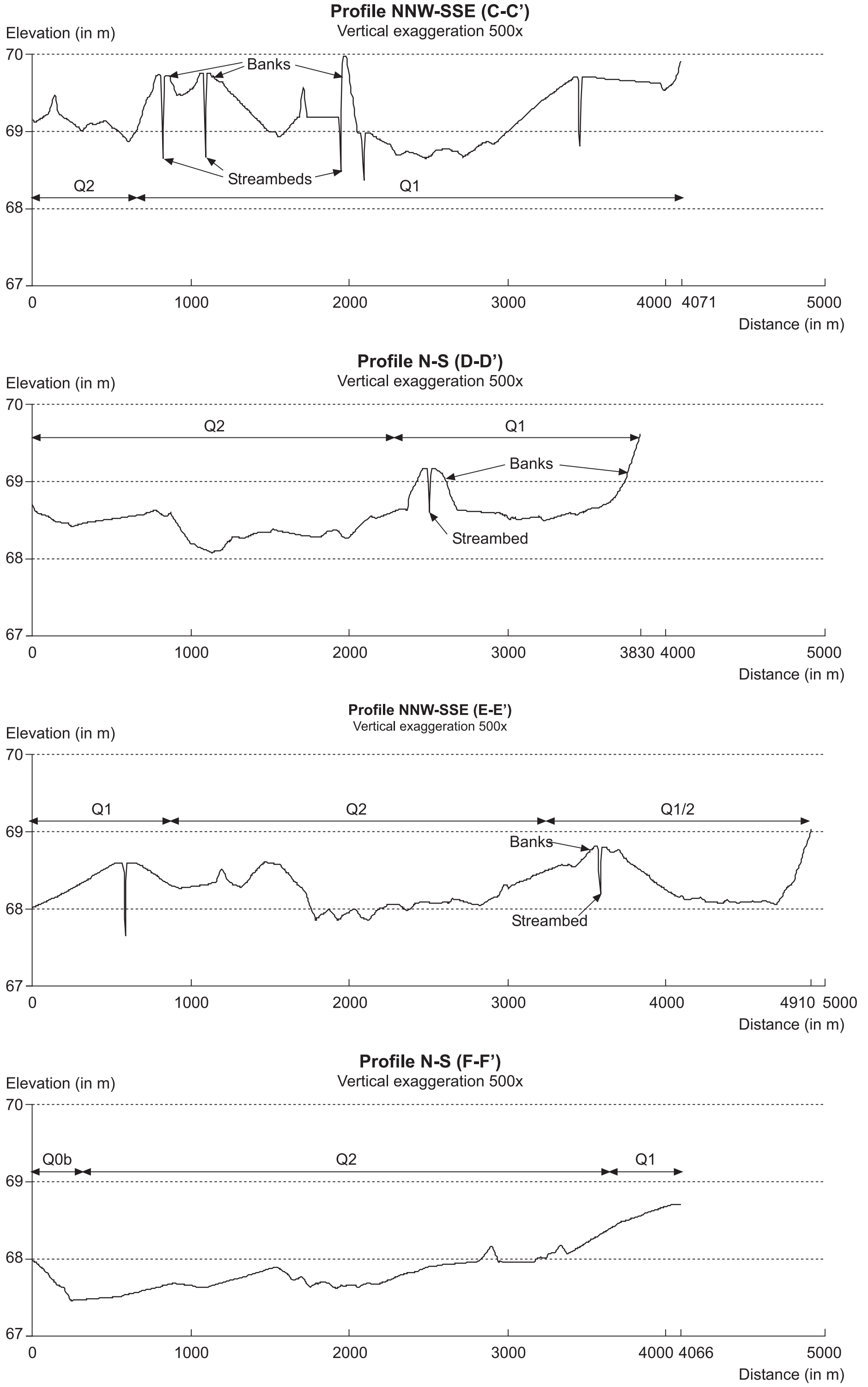


Figure 8. Profiles vertical to the main slope in the area. The profiles are parallel to the main dyke. For interpretation of the geological layers see Figure 6B.

Flooding dynamics in the Modulo Hato El Frío

In the study area water is stored in a number of sinks. The map showing the sinks is presented in Figure 9A. Upstream from the dyke a large sink is covering almost the entire area. Sinks also occur downstream from the dyke, but they are smaller and do not cover a large continuous area. In Figure 9B a simulation is given of sinks in the area if the dykes (central and lateral) did not exist, as before their construction. It shows that without dykes the upstream area is similar to the downstream area at the present time with sinks scattered over the area.

To compare the situation before dyke construction to the current situation, the amount of water that would be held in the modulo if all sinks were filled to their minimum overflow level was calculated for both DEMs. Without the dykes 2 270 227 m^3 of water are collected in the area and with the dyke 8 859 229 m^3, almost four times as much. The values given are for the entire modulo area. If only the upstream areas were compared the difference would be a lot larger.

The progressive filling of the area upstream of the dyke cannot be observed in Figure 9A. With the reduction of lowest overflow level, the inundation increases at different levels. The result can be observed in Figure 10. The values indicate the water level height that fills the respective area. When interpreting the profiles it should be taken into consideration that the sinks are filled by precipitation as well and sinks that are at different heights can be flooded at the same time.

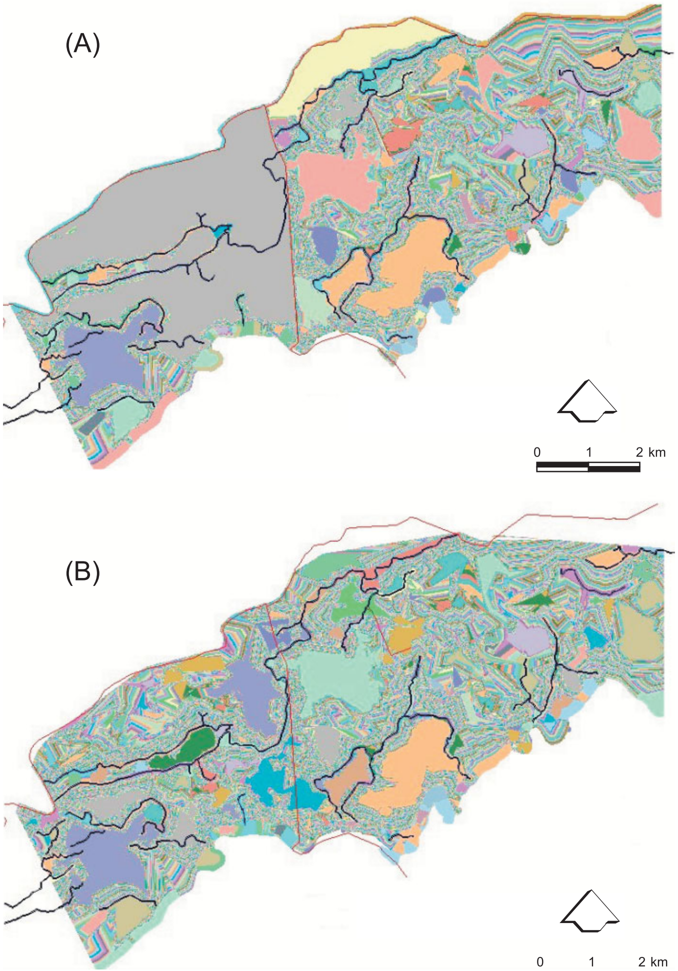


Figure 9. Filled sinks of the DEM with the dyke (A) and without the dyke (B). The larger areas of one colour are the sinks filled to the level of the lowest overflow. The main dyke and streams are indicated. Each surface of one colour delineates one area of internal drainage, which has been filled to its lowest overflow. The mingled areas are without sinks.

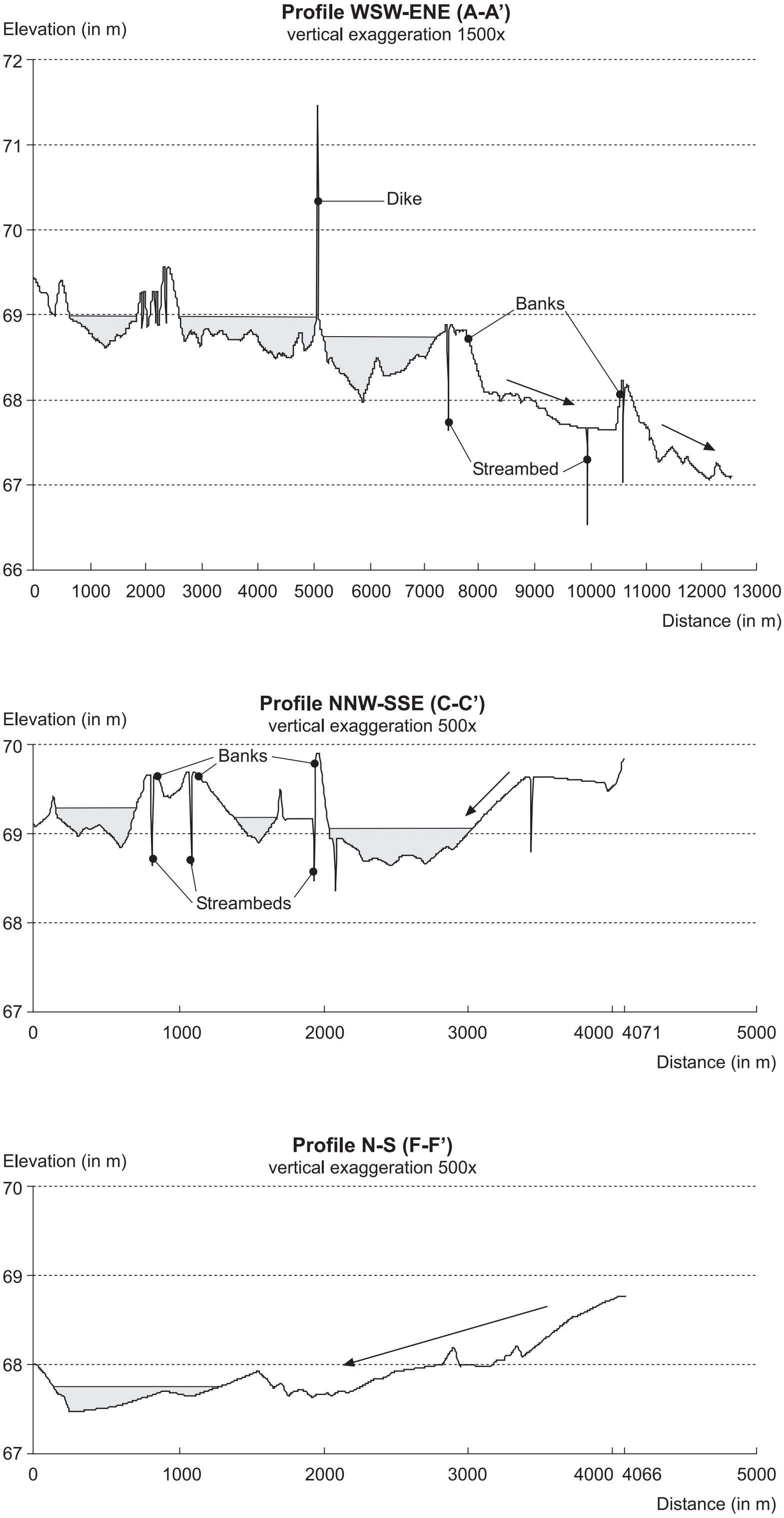


Figure 10. Profiles of filled sinks of the DEM. For the position of the profiles see Figure 6B.

Table II. Water volume of the flooded areas obtain from the classified radar images and the DEM. The water level heights were extracted from the DEM and the water depth is calculated as if the water were distributed uniformly over the area

	Dry season		**Transition**		**Wet season**	
Area relative to the dike:	**Upstream**	**Downstream**	**Upstream**	**Downstream**	**Upstream**	**Downstream**
Water volume (in 1000 m^3)	166	0	2 674	767	10 579	7 376
Water depth: (m^3/m^2)	0·01	0·00	0·12	0·02	0·49	0·21

Water volumes extracted from the radar image classification and the DEM

The quantity of water flooding the modulo area at different times of the year is shown in Table II. The values were calculated by combining the DEM with the classified radar maps. As the areas upstream and downstream from the dyke have different sizes, the average water height over the terrain was calculated for comparison.

In the transition season, the water level is only 11 cm higher than in the dry season. As the area is so flat small changes in the water level can cause the flooding of large areas. The difference of the water level between the transition and wet season is almost 60 cm and the water volume is more than tripled. Again, the effect of the dyke can be clearly observed.

At the end of the dry season the area downstream of the dyke has no superficial water and upstream there is also little superficial water. Upstream the inundation has decreased to only some small areas. In the transition period between the dry and the wet season the superficial water begins to collect in some downstream areas, whilst upstream large zones are flooded. In the wet season the majority of the modulo is inundated, leaving only small areas without superficial water.

Modelling of the inundation

As shown above, the modelling of the flooding downstream from the dyke is not possible, as the DEM does not cover the entire catchment area and the outflow from the area is unknown. Therefore the modelling of the inundation was performed only for the upstream area.

To model the inundation, the absolute water level heights obtained from fieldwork and the DEM upstream from the dyke were used. In Figure 11 the calculated water volumes for the different periods can be observed and compared to the volumes obtained from the radar images and the climatic data. The increase of water volume taken from radar is comparable to the volume extracted from the modelling. The diminution of the water at the end of the year is variable if compared between fieldwork and the climate calculation.

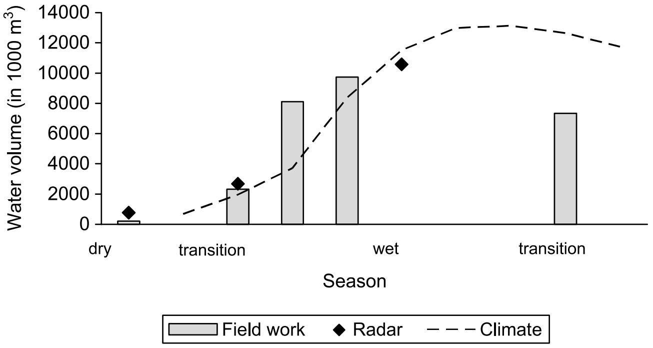


Figure 11. Comparison of the water volume calculated by different methods: from radar image classification, from fieldwork and from climatic data.

Discussion and Conclusions

The hydrological dynamics of the flooded savannahs of Apure situated in the southern Venezuelan Llanos appear to depend mainly on the presence of natural sinks or basins. The landscape of the area, including the presence of these sinks, originates from successive depositional events that took place during the Middle Pleistocene and Holocene period (Sarmiento and Pinillos, 2001). The oldest sediments (Q3), unlike the younger sediments, were not deposited as deltaic systems, but mostly by breaching (explayamento). Later they were tectonically changed, uplifted and eroded, erasing their original forms. The early Holocene depositions (Q2) have also been strongly eroded. They are the remains of abandoned riverbeds of the Arauca River. The old river banks are low (<1 m) and wide (200–1000 m). The orientation of the sediments is in an easterly direction, differing from the younger sediments, which are orientated in an ENE direction.

The middle Holocene sediments (Q1) were deposited around the large old riverbeds of the Arauca, which in actual time form the riverbeds of several smaller streams (caños). An interior delta was formed because of the low slopes in the area. The banks are relatively high (1 to 2 m) and between 200 and 1000 m wide. The overflow areas of silt material and natural levees are the predominant geomorphologic positions. The low banks are less than 1 m high and vary in width between a few metres and 150 m. These correspond to the deltaic arms of the overflow areas and breaching. Bajíos are found in 43 per cent of the area and the majority are overflow basins. The esteros cover around 18 per cent of the area and are decantation basins.

The youngest deposits (Q0) are found along the principal rivers and caños. The origin of the sediments in the case of the caños is the eastern part of the plain. As the deposits are of a young age they have not been eroded and have conserved their forms. Due to the very low slope in the area, the rivers that flow in the plain lose their ability to carry sediments very fast after leaving the mountainous area. They do not have very defined and stable river courses. The erosion of the sediments, the duration of which depends on their age, produced a progressive homogenization and levelling of the landscape. Also the very active current alluvial dynamics is dissecting the landscape and depositing new sediments.

Due to the virtual absence of slope in the area and the widespread presence of a hardpan that is highly impermeable in the soil profile, drainage is strongly limited and significant amounts of water tend to accumulate in the natural sinks from where they are progressively lost to the atmosphere by evapotranspiration. The capacity of the system to store water depends on the size of these natural sinks, which are formed and delimited by the levees of the fluvial system (active and former rivers and streams). An intricate network of levees can be observed in the area forming natural dykes and sinks of different sizes and capacities to store water. A few centimetres of difference in the height of a levee can produce large differences in the size of the sink, due to the very low slope of the area. Using the DEM the relationships between the heights of the levees, the size of the sinks and the depositional epoch of sedimentation can be clearly observed. In landscape dominated by older sediments (Q2 in the area), where the banks have been eroded over a longer period of time, the landscape is more homogeneous. The levees are relatively lower and consequently the size of the sinks and their capacity to store water are reduced compared to the younger sediments (Q0 and Q1) where the banks are higher and bigger sinks are formed. Consequently on younger sediments larger areas are flooded and the water level is higher. The relationships between the geological epoch and the predominant ecological type of savannah have been previously observed by Sarmiento and Pinillos (2001), but our results clarify the effect of the depositional epoch on the hydrological regime, explaining the different capacities to store water in terms of the characteristic of the sinks. Hudson and Colditz (2003) also find in the Pánuco basin in Mexico that although floodplains are often portrayed as homogenous (flat) surfaces subject to flooding, the duration of flooding varies due to the geomorphic complexity of large alluvial valleys and not all surfaces are inundated.

To check whether the calculated volumes are in a reasonable range, theoretical water volumes were calculated using the hydrological balance of Mantecal. Even though the precipitation in the study area is variable, general tendencies can be extracted from the data of the long-term average year. From April onwards the water level for each month was calculated and multiplied by the area of the modulo. For the calculation a totally dry area at the end of the dry season was presupposed. The comparison of the calculations downstream from the dyke shows that all water volumes from the climatic data are much higher. In the wet season the water volume derived from the radar classification was 7 376 000 m^3 and from the climate calculations it was 13 734 000 m^3 or almost twice as much (Figure 11). This indicates that without the dyke the runoff is probably relatively high and the estimation from climatic data without runoff is not valid. On the other hand the comparison of the water volumes upstream from the dyke shows that the general tendency from the dry to the wet season is similar in both cases.

The main effect of the dykes on the hydrology is that natural sinks are enlarged or new sinks are created, considerably increasing the amount of water that can be retained. The ecological consequence is that the relative proportions of the different types of savannah ecosystems change, decreasing the extension of the hyperseasonal savannah and increasing the semiseasonal savannahs. In a previous study on the flooding savannahs of Apure, covering an area of approximately 7500 km^2, Chacón-Moreno (2000) showed that between 1960 and 1988 semiseasonal savannahs increased their extent by 4·6 times due to the construction of dykes. An interesting aspect is that dykes are not creating new types of environments but changing the proportion of the existing ones. From an ecological point of view this is important because the creation of new habitats can promote the invasion of foreign species, but the extension of an existing ecosystem would not produce this effect. However, the spatial pattern and temporal offer of resources are modified by the dykes and the global ecological effects on wild fauna and ecosystem functioning can be important and have to be evaluated. From an agronomical point of view the primary productivity of the area increases, as the semiseasonal savannahs are the more productive (Sarmiento, 1984; Bulla, 1980).

The dykes also have an effect on the temporal flooding dynamics, causing the upstream area to flood earlier. Also the flooding period is extended during the dry season, despite the very high evaporative demand during this season, due to the increase in the water level height. Evapotranspiration during the dry season can be as high as 8 mm day^{-1} (ECOSA, 1980), so an approximate level of 1 m of water is needed to maintain the inundation over the four months of the dry season.

The positive effect of the dyke on water retention in the upstream area is accompanied by a negative effect downstream. As the overland flow from upstream is cut off, sinks in this part of the modulo are only filled with rainwater and consequently the area close to the dyke dries out faster than in the natural situation. The consequences of the dyke for land use are multiple. On the one hand, inundation lasts longer, providing water when downstream areas are already dry and enabling the cattle to pasture these areas, but on the other hand inundation can reach far upstream. This could cause a lack of available land for grazing at the peak of the wet season, as banks that formerly were used by the cattle in the wet season are now flooded. This disadvantage is reduced if the dykes have floodgates, as is the practice in other parts of the flooding savannahs of Apure. Also the areas downstream can be used for grazing when the upstream areas are already flooded.

Comparison of the results of flood modelling on the basis of fieldwork data and the radar classification shows that these methods arrive at comparable values. The values derived from the climatic data (water balance method) also show that predicted volumes of water are roughly similar to the water estimated by the other methods for the period from the dry to the wet season. Nevertheless, a direct comparison is not possible because the climatic data for the years of the study are not available and when using the mean values the strong annual fluctuations in precipitation in the study area have to be considered. Comparing the results of the water balance method compared with the calculation using the DEM shows more pronounced differences: more water is predicted by the water balance method. This is probably not due only to the climatic variations between years. The hypothesis is that runoff plays a more important role after the sinks in the area are filled and in the water balance method runoff and drainage were neglected.

The modelling of the flooding dynamics shows that a detailed DEM could provide the possibility to model the effects of a dyke before its construction. Different scenarios can be calculated for dry and wet years and various possible positions and heights of the dykes can be tested. This can help to decide on the impact of a dyke and on the best location. Also the maximum height of overflow can be determined so that the flooding does not exceed the desired zones. The desired flooded zones would have to be defined, to maintain enough pasture in the dry season as well as in the wet season. If the inundated areas are too large there would be a shortage of grassing areas in the wet season and if too small the shortage would be in the dry season.

From a methodological point of view, the results show that when a detailed DEM exists, the water dynamics in an area can be modelled with relatively little fieldwork. The requirements are that the DEM covers the entire catchment area and that the data have sufficient vertical and horizontal accuracy. This is also one of the biggest problems when working in very flat areas, because often contour lines and height points are not very dense in the available topographic maps (Marks and Bates, 2000). Although a DEM can also be created with digital photogrammetry techniques (Baily *et al*., 2003; Lane *et al*., 2000), the required accuracy is frequently not met by the data. This is especially the case when working in countries where very little topographical data and few large-scale aerial photographs are available, as is often the case within humid tropical areas (Hudson and Colditz, 2003). Therefore the developed method using aerial photograph interpretation and a geological map in combination with GPS measurements could be an alternative for these environments. The results have shown that although the DEM is not an 'exact' reproduction of the topography of the area, it allows modelling of the flooding dynamics and the results resemble those obtained from the radar image classification.

The construction of the DEM allows clarification of the relationship between the epochs of sedimentation and the relief forms. These relationships could be used to deduce important aspects of the relief of other zones by extrapolating the relative height information from the profiles. This information could be combined with the data from a geological map and aerial photograph interpretations, and the overall slope of an area could be extracted from available maps. This method would not give detailed information on the relief, but it would help identify the barriers, such as levees, for superficial runoff. The possibility of extrapolation needs to be explored further, but it could prove interesting for an area where DEMs with the precision and scale of our study are difficult if not impossible to find.

Acknowledgements

The study formed part of an international project 'Ecological bases for the sustainable management of tropical flooded ecosystems: Case studies in the Llanos, Venezuela and in the Pantanal, Brasil' which was financed by the European Union INCO DC programme and took place between 1997 and 1999 (ERBIC 18CT960087). We would also like to thank Dimas Acevedo for the many discussions and Christof Fischer for his valuable help during the fieldwork. Special thanks also go to the Hato El Frío for their hospitality and support.

References

Baily B, Collier P, Farres P, Inkpen R, Pearson A. 2003. Comparative assessment of analytical and digital photogrammetric methods in the construction of DEMs of geomorphological forms. *Earth Surface Processes and Landforms* **28**: 307–320.

Betancourt R, Ortega M, Bustamante A. 2001. Unidades de manejo intensivo de forrajes. *Venezuela Bovina* **47**: 11. Available at: www.ppca.com.ve/vb/ [1 December 2003]

Bulla L. 1980. Ciclo Estacional de Biomasa Verde, Matéria y Raices en una Sabana Inundada de Estero en Mantecal, Estado Apure. *Acta Científica Venezolana* **31**: 339–344.

Burrough PA, McDonnell RA. 1998: *Principles of Geographical Information Systems*. Oxford University Press: New York.

Chacón-Moreno EJ. 2000. Landscape change by embankment of the flooded savannah Llanos de Orinoco: a land unit approach. In *Landscape Ecology Applied in Land Evaluation, Development and Conservation, Some Worldwide Examples*, van der Zee D, Zonneveld IS (eds). ITC Publication 81. IALE publication MM1.

ECOSA. 1980. *Estudio Agrológico de Gran Vision: Estado Apure. Informe General*. Ministerio del Ambiente y de los Recursos Naturales Renovables: Caracas, Venezuela.

Hudson PF, Colditz RR. 2003. Flood delineation in a large and complex alluvial valley, lower Pánuco basin, Mexico. *Journal of Hydrology* **280**: 229–245.

Jongman RHG, Smith JK, Chacón-Moreno EJ, Loedeman JH. 2005. *Flooding Processes in the Llanos de Orinoco (Venezuela)*. Wetlands (in press).

Lane SN, James TD, Crowell MD. 2000. Application of digital photogrammetry to complex topography for geomorphological research. *Photogrammetric Record* **XVI**(95): 793–821.

Malagón D, Ochoa, G. 1980. *Caracterización mineralogical, micromorfológia y de génisis del suelo en las planicies cuarternarias de la region sur de San Fernando de Apure, Edo Apure, Venezuela*. CIDIAT: Mérida.

Marks K, Bates P. 2000. Integration of high-resolution topographic data with floodplain flow models. *Hydrological Processes* **14**: 2109–2122.

Pinillos M. 1999. *Modelo hidrológico de simulación en los Llanos inundables del estado Apure. Una aproximación desde la dinámica de sistemas*. MSc Thesis, CIELAT, ULA, Mérida.

Rivas JA, Rodriguez JV, Mittermeier CG. 2002. The Llanos. In *Wildernesses*, Mittermeier RA (ed.). CEMEX: Mexico; 265–273. Available at: http://pages.prodigy.net/anaconda/llanos.htm [22 November 03].

Sarmiento G. 1983. The savannas of tropical America. In *Tropical Savannas*, F. Bourlière (ed.). *Ecosystems of the World 13*. Elsevier: Amsterdam; 245–288.

Sarmiento G. 1984. *The Ecology of Neotropical Savannas*. Harvard University Press: Cambridge.

Sarmiento G, Pinillos M. 2001. Patterns and processes in a seasonally flooded tropical plain: the Apure Llanos, Venezuela. *Journal of Biogeography* **28**: 985–996.

Schargel R, Gonzalez RA. 1972. *Estudio Agrologico preliminar: Sectores Bruzual y Mantecal, Estado Apure*. Ministerio de Obras Públicas: Caracas.

Tamisier A, Dehorter O. 2000. *Fauna of the Llanos and Pantanal. Ecological basis for the sustainable management of tropical flooded ecosystems. Case studies in the Llanos (Venezuela) and the Pantanal (Brazil)*. Centre d'Écologie Fonctionelle et Evolutive CNRS: Montpellier.

Tejos R, Schargel R, Berrade F. 1990. Characerísticas y perspectivas de utilización de sabanas inundables en Venezuela. In *Las Savannah Americanas*, Sarmiento G (ed.). Las Sabanas Americanas, Fondo Editorial Acta Cientijica Venezolana. Caraca, Venezuela 141–162.

Vivas L. 1992. *El Cuaternario*. Universidad de Los Andes: Mérida.