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ASSSESSING FLOODING PATTERNS IN LLANOS OF THE APURE REGION (VENEZUELA) USING RADAR IMAGES

PROCESOS DE INUNDACIÓN REGIONAL EN LOS LLANOS DE APURE (VENEZUELA)

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ABSTRACT

In the flooding savannas of the Llanos del Orinoco water is the main factor determining the ecosystem and its changes. During flooding, the water level and flood duration depend highly on the relative height position of the ecosystem unit. To understand the spatial processes in the ecosystem it is important to know the water dynamics. The Llanos is an alluvial basin with sediments from the lower-middle Pleistocene until the present. Terrain differences within de Llanos between the Arauca and the Apure River are small. A flood map has been constructed for the regional level and for the area of the hacienda Hato el Frio. For the analysis of the flooding pattern use has been made of radar images. Field data have been collected in the area of hacienda Hato el Frio to be used for interpreting the radar images. In the flood map, an increase of inundation from the dry to the wet season can be observed. At the end of the dry season few areas are covered with water; in the wet season approximately half of the area is inundated. Gallery forests were extracted from a classified Landsat image. The methods applied appear to be valid to the classification and monitoring of inundation, but only the spatial extent is obtained with this method as the radar images do not measure water depths.

Key words: Apure, savanna, river floodplain, radar images, flooding regime, seasonal impacts, hyperseasonal savanna

RESUMEN

En las sabanas inundables de los Llanos de la cuenca del Orinoco el agua es el factor principal que determina el ecosistema y su cambio. Durante la inundación, la duración y nivel del agua dependen en gran medida de la altura relativa de la unidad ecosistémica. Para entender los procesos espaciales en el ecosistema es preciso conocer la dinámica del agua en el área. Los Llanos son una planicie con sedimentos del pleistoceno bajo-medio hasta el holoceno donde las diferencias del terreno son muy pequeñas. Un mapa de la inundación fue construido para el nivel regional y para el área del Hato el Frio. La base para el análisis de la inundación fueron imágenes de satélite cuya interpretación fue facilitada por los datos de campo del área de la hacienda Hato el Frio. En el mapa de la inundación se observa el aumento de la zona inundada entre el periodo seco y húmedo. A finales del periodo seco pocas áreas se cubren de agua siendo en el periodo húmedo cuando aproximadamente la mitad del área es inundada. Los bosques de galería fueron extraídos de la imagen Landsat una vez clasificada. Los métodos aplicados para la clasificación y la supervisión de la inundación de cualquier área parecen ser validos. Sin embargo, sólo la dimensión espacial se obtiene con este método.

Palabras clave: Apure, sabana, tablas fluviales, régimen de desbordiamiento, impactos estacionales, sabana hiperestacional

INTRODUCTION

Wetlands occupy 6% of the earth's land and freshwater surface and play an important role in maintaining the stability of the global environment. They nurture hundreds of species and provide critical habitat for a wide variety of wildlife. They are important for regional climate as they provide humidity for the surrounding landscape. For sustainable management of flooded tropical ecosystems it is important to know what changes do occur through land and water management. Hydrologically nearly undisturbed river systems such as the Apure and Arauca in the Llanos del Orinoco are important to study as a baseline for the impact of man on river systems as well as climate variability in tropical wetlands. An EU Research project has been set up to study indicators for sustainable management of tropical humid ecosystems with the objective of understanding the processes in the Latin American savannas and human impact on it (project INCO-DC ERBIC18T960087). The general objective of the project is the analysis of biodiversity change due to land use change - dike development and intensification of cattle breeding - and climate change in river wetlands on ecosystem and landscape scale. A fundamental part of the project is to analyze regional flooding patterns in time and space as a basis for modeling water flows and understanding the human impact on the system. The maps of the flooding regimes are used in the modeling the inundation patterns and related ecology at the local level. The project has been carried out from November 1997 until February 2000. In this paper the analysis of the flooding patterns at the regional level is presented as well as a discussion on the tools and their difficulties in recognizing flooding patterns. Other part of the research, such as the detailed flooding and the impact of dikes at the local level is dealt with in another publication (Smith *et al.* 2006).

A part of the Venezuelan Llanos is the savanna of the Apure situated in the Orinoco river basin. The savanna of the Apure is about 16.000 km^2 and is located between the rivers Apure and Arauca in the Apure State (Figure 1). In 1966 schemes were made to build dikes in this area for retaining water in the wet season for bridging the drought of the summer months. Over the past thirty years these schemes have led to local changes in the water storage, land-use and ecosystems. In the savannas of the Apure and Arauca a study area of 100 x 100 km^2 has been analyzed, representing the approach at the regional level. Within this larger area an intensive study area for fieldwork is located in the hacienda of Hato el Frio in the savanna of the Apure.

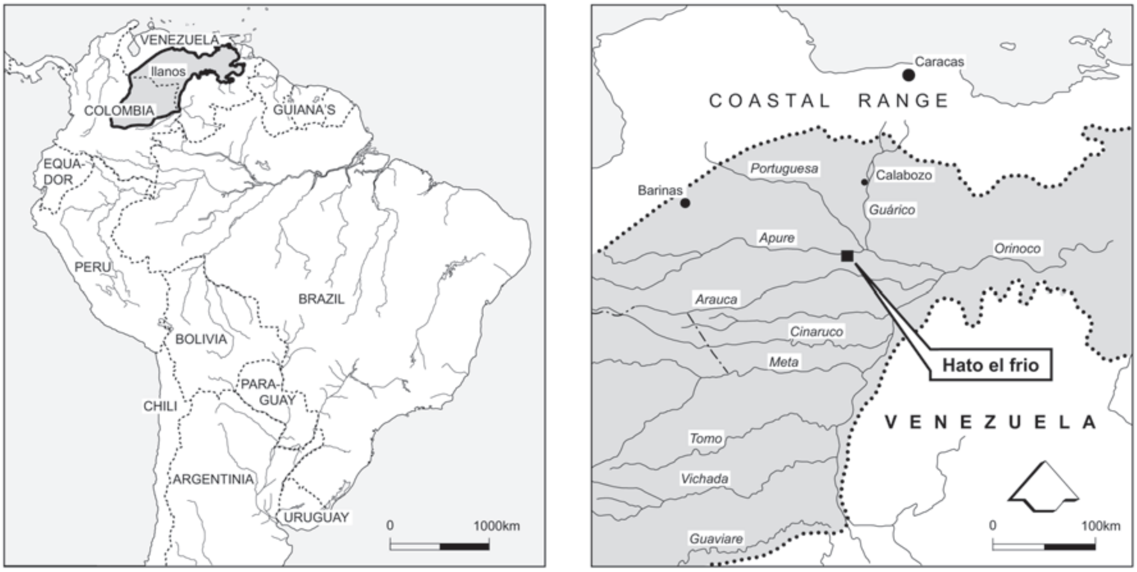


Figura 1. Location of the Llanos de Orinoco. The research area is located between the rivers Apure and Arauca. The Hacienda of Hato el Frio is situated near the banks of the Apure (adapted after Sarmiento 1983).

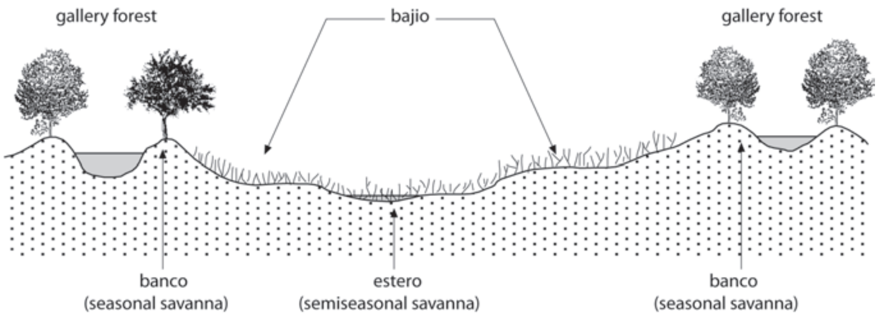


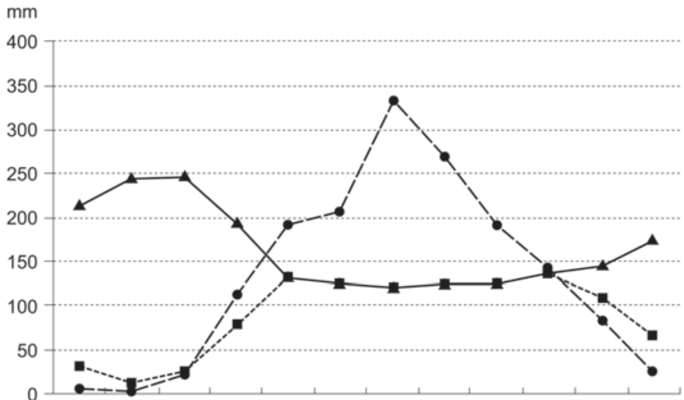
Figura 2. Physiographic units and their related vegetation before dike construction (side view). The system consists of three basic units, (1) bank/levee: banco (seasonal savanna), (2) flat: bajío (hyperseasonal savanna), and (3) basin: estero (semiseasonal savanna), based on the division by Sarmiento and Pinillos 2000.

THE ENVIRONMENT OF THE LLANOS OF THE APURE

Climate

The Venezuelan Llanos are situated in the upper and middle reach of the Orinoco river basin in Venezuela and Colombia. The Llanos form part of a large basin, a geo-synclinal formed in connection with the Andean-Caribbean epirogenesis beginning in the late tertiary. The basin has been filled with alluvial sediments (Vivas 1992). Due to the nearly flat character of the area, the rivers in the plain have lost their capability to carry large sediment loads over long distances after leaving the mountain area of the Andes and the coastal range. River courses are not stable but partly braiding and partly freely meandering.

The study area has a homogeneous, macrothermic and isothermic climate. Monthly mean temperatures are between 25,4°C in July to 28,5°C in March, the mean precipitation is between 5,1 mm in January to 329,2 mm in July, while the mean evapotranspiration ranges between 141,7 mm in June and 325,2 mm in March (Sarmiento 1990). The savannas of the Apure are located on alluvial overflow plains dated from late Pleistocene to early Holocene, that have modeled the landscape in a system of physiographic units:



Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
5	3	21	110	191	205	336	269	192	144	88	26	Pecipitation
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

Figura 3. Climate diagram of Mantecal; ETP: potential evapotranspiration; ETR: actual evapotranspiration. (ECOSA, 1980)

(1) levee: banco, (2) flat: bajío, and (3) basin: estero (Figure 2). They can be distinguished according to their local relief (Silva and Moreno 1993).

There is spatial and temporal variation in flooding. As the main water source of the inundation is precipitation within the river basin, the yearly rainfall and its distribution over the year is an important factor for the determination the inundation process. In Figure 3, climate data are given for Mantecal (7°34'N, 69°8'W), situated in the centre of the regional study area. The flooding process reflects in part the precipitation pattern and in part the river discharge from the mountains. To the Southwest large areas are already flooded in May, whereas to the Northeast the main flooding is in July and August. Differences in precipitation alone do not explain spatial distribution of the inundation, but factors such as overland flow and river discharge have to be taken into account as well.

Geomorphology

The alluvial accumulations are principally from the rivers Arauca, Apure and Uribante and Sarare. The last two form in their confluence the Apure River. In the study area, the sediments correspond to the upper Holocene to the lower-middle Pleistocene. Older sediments (Q3) were transported further than the younger sediments and deposited almost in the entire area and later covered by younger sediments (Q1 and Q2) in a discontinuous form. In contrast to older epochs of sedimentation the youngest sedimentation (Q1-Q0) conserves its original forms, produced by fluvial dynamics as natural levees or banks, flat overflow areas and decantation basins (ECOSA 1980, Vivas 1992). The banks are formed from coarse sediments (sands). As in all river systems silt sediments were deposited in the hyperseasonal and semiseasonal savannas (Sarmiento 1984, Sarmiento and Pinillos 2001). The sediments of Q3 have been deposited by breaching (explayamento). Later they have been changed tectonically, uplifted and eroded, erasing their original forms. In the study area Q3 is found in the Northwest of the study area, where the sediments generally form flat areas, locally with undulations. Q2 deposits have been fossilized and have been erased by fluvial erosion. They are remnants of abandoned riverbeds of the Apure and Arauca River and they originate from overflow and erosion afterwards. Intense deflation modified the relief and the sands from the riverbanks were deposited as dunes covering natural levees and bajíos. Q1 sediments were deposited along the large old riverbeds of the Arauca, which at present form the riverbeds of several smaller streams or caños. The banks are relatively high, 1 to 2 m and between 200 and 1.000 m wide. The overflow areas of silt material and natural levees are the predominant geomorphologic positions. Bajíos are found in 43% of the area and the majority is overflow basins. The esteros cover around 18% of the area and are decantation basins. The deposits of 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 young age; they have not been eroded and have conserved their forms (Smith *et al*. 2006). According to Sarmiento and Pinillos (2001) the genesis and dynamics of the various land forms and soils throughout the Quaternary, provide the key to their particular hydrology, and determines the kind of plant formation able to occupy each habitat, thus explaining the complex pattern of quite different ecosystems found in the region.

The soils are homogeneously dystrophic as a result of their origin and the intensive leaching. The availability of soil moisture during the dry season and the low-level nutrient status of the soil are the two main ecological constraints limiting natural and agricultural productivity.

Open savannas and grasslands are the main land cover in the study area. Forest only occurs along rivers and along dikes in the 'modulated' area, as a 'gallery forest'. In hyper-seasonal savannas, trees are restricted to small, better-drained parts as remnants of riverbanks or local sand dunes. In the better-drained, seasonal savannas, trees are restricted to areas where the water table is within reach of the root system.

It appears difficult to maintain cattle breeding with the present low farming intensity and size of holdings. In the Llanos this means that intensification takes place: the building of banks and polders "modulos". These changes in land use and land structure are changing the environmental conditions in the river basin and for the wildlife populations in these areas.

METHODS

General approach

The research is carried out in a regional study area within the savannas between the Apure and the Arauca; field work has been carried out on the level of a modulo within the hacienda

Tabla 1. The qualitative description of the different ecosystems, their changes during the year and the expected backscatter coefficients. The factors that influence the backscattering most in each season are highlighted in grey.

Ecosystem	Micro-relief	Dry season			Transition dry-wet season			Wet season			Transition wet-dry season		
		Soil	Vegetation coverage	Bs value	Soil	Vegetation coverage	Bs value	Soil	Vegetation coverage	Bs value	Soil	Vegetation coverage	Bs value
Hyperseasonal savanna	Rough, Worm mounds	Dry	Low – none	Medium	Moist	Low-Medium	High	Wet-flooded	Low	Low	Moist	High	Medium
Semiseasonal savanna	Fine	Moist	Medium-high	Medium	Moist-flooded	Low	High and low	Flooded	High	Medium	Flooded	High	Medium
Seasonal savanna (without gallery forest)	Fine	Dry	Low – none	Medium	Dry-moist	Medium-low	Medium	Moist	High	Medium	Moist-dry	High	Medium

Hato el Frio. A basic requirement for the analysis of spatial data is referencing to the same co-ordinate system. Special attention has to be paid to this process for combining different spatial data sources. 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 the 7th of May 98, corresponding to the transition period between the dry and wet season, the 20th of August 98 for the wet season and the 3rd of December 98 for 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 was very dry and there was very little flooding. The pixel size of the images is 30 x 30 m. The radar images were processed and classified with ground control areas and flood maps were created for the different seasons. The images cover an area of 100 by 100 km^2, which are approximately 60% of the total study area. The intensive study area, the modulo of the hacienda Hato El Frio, is inside the image coverage.

Field data were collected in the intensive study area of the Hato el Frio in May 1998, December 1998 and February 1999. In February 1999, field data was also collected outside the intensive study area. For August 1998, no field data could be collected due to high flooding of the area and broken dikes that should be used to access the field. Later examination when access was possible it showed that all field measure points (rulers) appeared to be flooded in that period, so the problem of no access did not affect the field measurements. The data was used to help interpret the radar images.

All collected data was introduced into an Access database and different point maps were created, representing the information (flooding, water content, micro-relief, etc.). These maps were overlaid with the radar images to interpret the images and to control the results of the classification.

Georeferencing

All data are referenced to the local co-ordinate system (UTM, Ellipsoid: International1924/ Provisional South American 1956; datum point La Canoa). The basis for the georeferencing at regional scale is the topographical map 1:100.000. These are considered sufficient accurate to be used as a basis for this scale.

Georeferencing at the regional scale was carried out with help of Landsat images. The basis for the referencing of all images at regional level is the georeferenced Landsat image from 1988. This image was georeferenced with 40 ground control points taken from the 1:100.000 topographical maps. Then an affine transformation (sigma = 25m) was performed. The control points covered the entire area and were distributed as even as possible over the image. The georeferencing was done in ILWIS using 170 ground control points from the Landsat image and then transformed with an affine transformation (error approx. 12.5 m). By co-referencing the images, the same referencing model can be applied to all radar images.

Regional flooding maps

All radar images were imported and processed in Erdas Imagine. They were georeferenced and

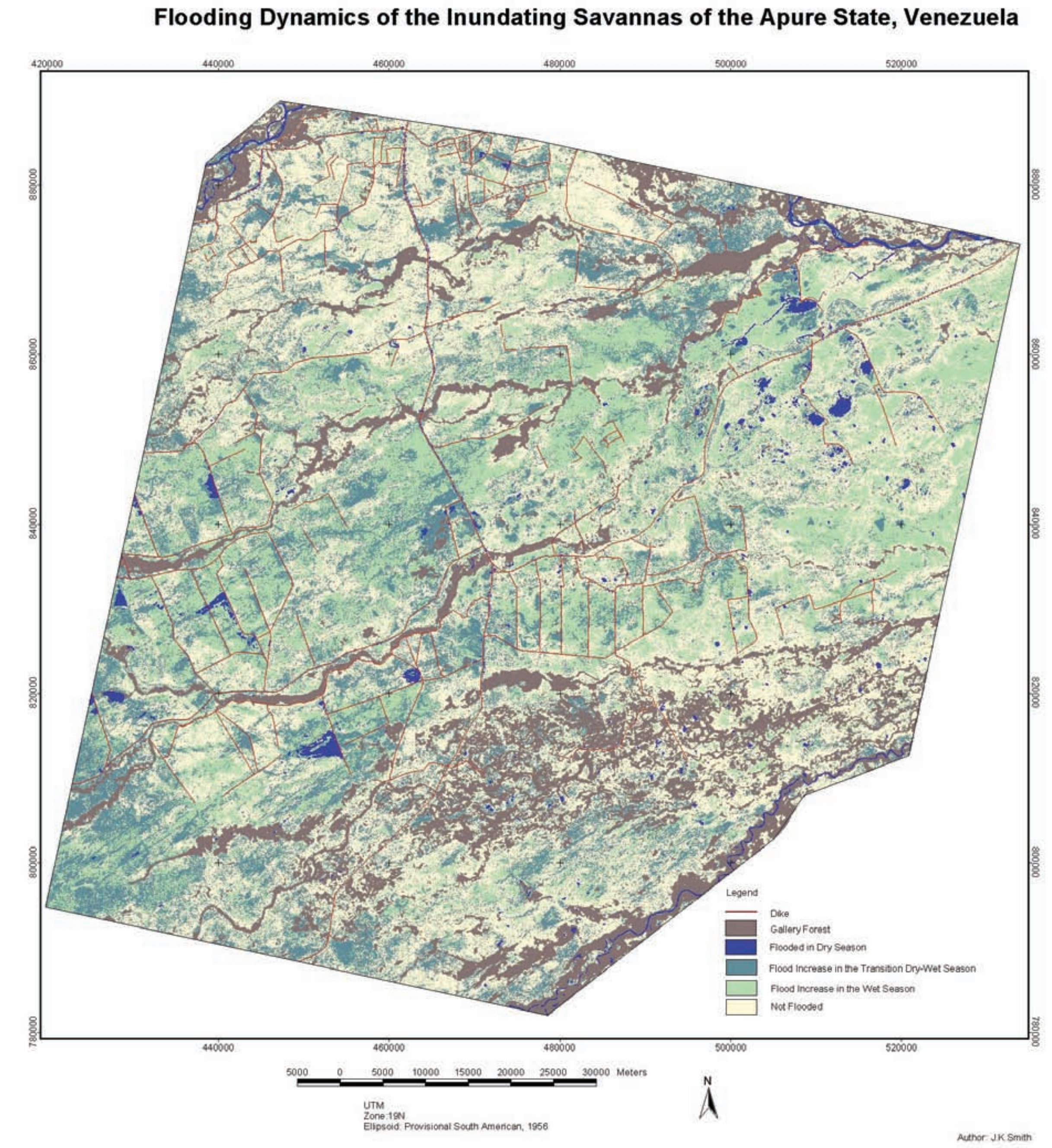


Figure 4: Flooding map of the inundating Savannas of the Apure State based on analysis of radar images. The legend indicates areas that are permanently flooded; those that are being flooded in the transition period and wet period and areas that are never flooded.

filtered by MAP Gamma, a Maximum A Posteriori filter with a 3 x 3 window to reduce the speckle noise. The images are delivered as 16 bit files with digital numbers (DN). The DN values were converted to backscatter values, sigma nought (σ^0) and expressed in decibels (dB). For the method of the derivation of sigma nought in PRI images (Laur *et al*. 1998). This process also results in data reduction.

From general climate models and regional land use information it can be concluded that at the end of the dry season in the seasonal and hyperseasonal savanna the soil is dry and the vegetation cover is low or zero as mostly the vegetation is burnt (Sarmiento and Pinillos 2000).

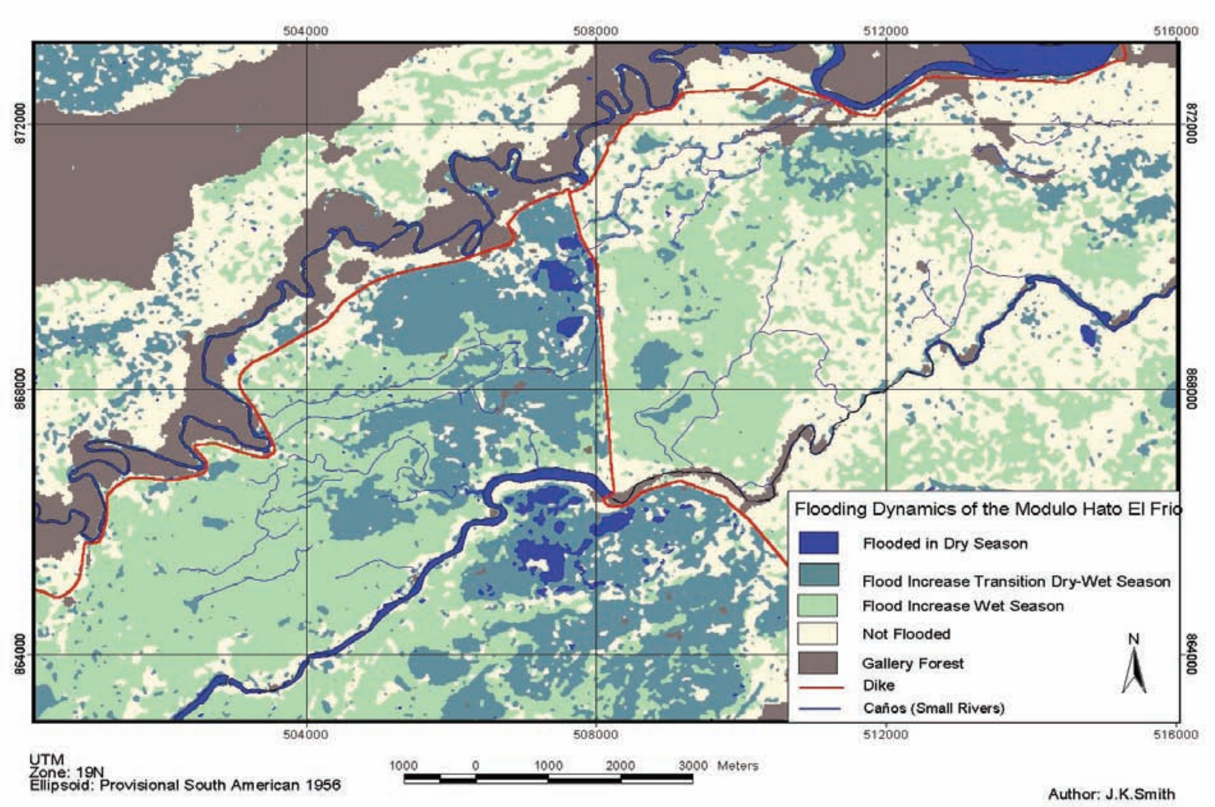


Figure 5: Flooding map of the Modulo Hato El Frio based on analysis of radar images. The legend indicates areas that are permanently flooded; those that are being flooded in the transition period and wet period and areas that are never flooded.

Where the microrelief is rough the backscattering is medium. As the rainy season begins the backscattering increases with the humidity of the soil, but when vegetation develops the backscatter values decrease. If flooding is high and the above ground vegetation dies, the backscatter is very low. If the vegetation is dense, flooding will not influence the backscatter and the value will be intermediate. As the three main physiographic units in the area have different hydrological regimes over the year, a straightforward interpretation of the radar images is not possible (Table 1). Backscatter values of an inundated area at one time of the year may not show inundation at another date although they are inundated, but also covered with floating vegetation.

The classification of the images was first performed on the intensive study area at the Modulo Hato El Frio and later applied to the entire image. The results of the classification of the whole area were compared to the results of the fieldwork done outside the intensive study area in February 1999. Even though this part of the fieldwork was done at a date different from the time of the recording of the images, the results could be used to some extent; as e.g. if the area was flooded in February 1999 it also was flooded in August 1998.

For the interpretation of the images first an automatic classification was applied, classifying each image into 14 classes. The created classes were then reclassified by overlaying the point maps with the results of the fieldwork and by using our knowledge on the area. The classes “inundated” and “not inundated” were assigned to the automatically created classes. For the classification of the images and production of the flood maps, a synthetic layer was generated. A synthetic layer is the product of two or more images that are joined by a mathematical function, producing a new image. The layer was the product of the May 98 scene subtracted from the August 98 image. This image was made to be able to separate the banks (seasonal savanna) from the esteros (semiseasonal savanna) in August. In the areas that have been inundated for a longer period, vegetation adapted to inundation has developed. The vegetation in these flooded

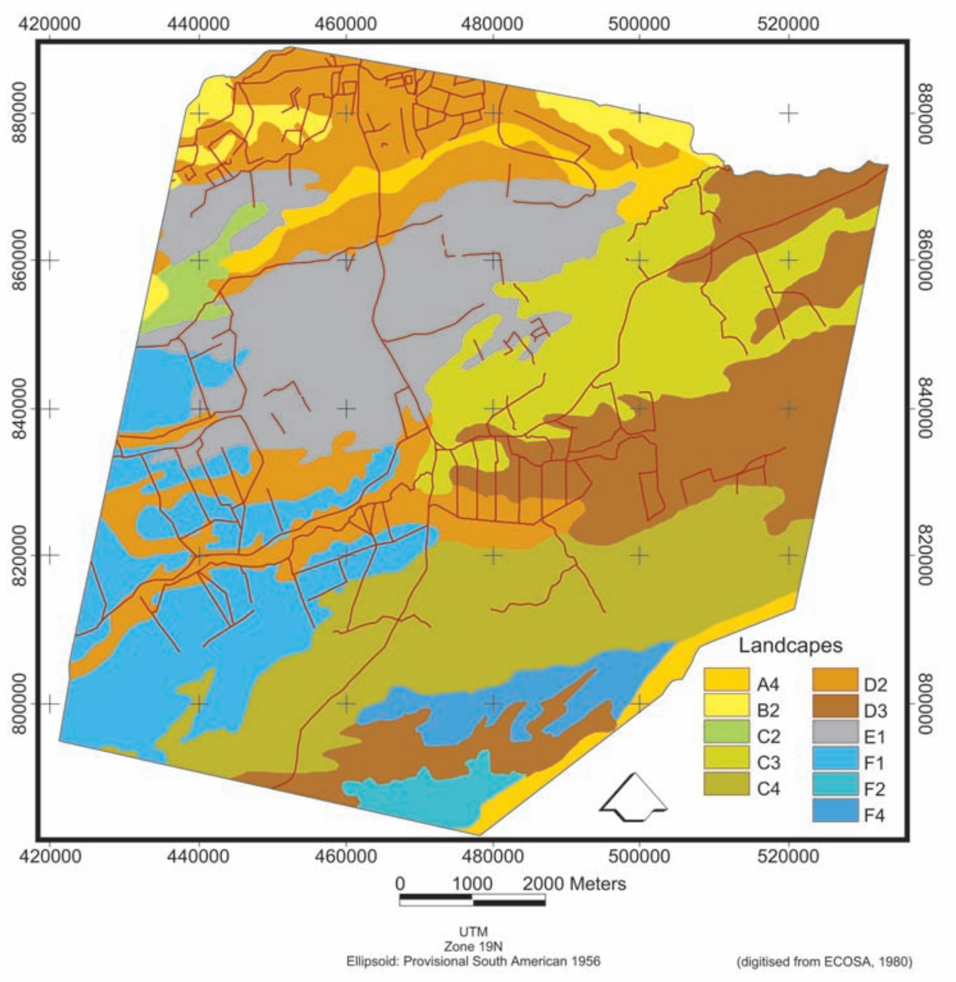


Figure 6: Map of the principal landscapes in the study area. Explanation of the landscapes is given in Table 2. The red lines are dikes.

areas has a thick coverage of water hyacinths (*Eichhornia crassipes* (Mart.) Solms). This makes the flooding "invisible" for microwaves and the backscatter will only depend on the vegetation. These areas have similar backscatter values as the zones, which are never flooded, as is the case for the higher banks. The synthetic layer enables the separation of these areas.

The inundation map therefore is a combination of maps from the four seasons. For the image of May 1992 all pixels with backscatter values (dB) lower than -12 dB were considered flooded and map was created showing the flooded and none flooded areas. For the image of May 1998 pixels lower than -14 dB enter the class "flooded". For the map "Flooded in May 1998", the classes "flooded in May 92" and "flooded in May 98" were combined. The map "Flooded in August 1998" is a combination of all four scenes. From the August scene all pixels lower than -15 dB and from the December image the pixels lower than -20 dB were entered in the class "flooded in August 98". The classes "flooded in May 92" and "flooded in May 98" from the first two scenes also were assigned to this class. Apart from these scenes the synthetic layer August 98 minus May 98 was utilized. From this layer all pixels with values higher than 4 and lower than -3 were considered flooded. The image of December was used under the assumption that areas that are flooded in December have to be flooded in August.

RESULTS

Regional flooding maps

The final maps, Flood Map of the Inundated Savannas of the Apure State (Figure 4), and Flood

Table 2. Description of the principal landscapes and the percentage of inundation for May and August 1998 based on radar interpretation and ground truth data. The landscapes (column 1) are depicted in Figure 6. The types in the column chronology are from upper Holocene: Q0a, lower Holocene: Q0b, upper Pleistocene: Q1, middle Pleistocene: Q2, lower Pleistocene: Q3. The column Inundation shows the likelihood for inundation as estimated on expert judgment (ECOSA, 1980). The columns Flooded May98 and Flooded Aug98 present the actual flooded area in May and August 1998. For explanation of the chronology see Sarmiento and Pinillos (2001).

Landscape	Sector	Chronology	Relief	Geomorphology	Inundation	Flooded May98 (%)	Flooded Aug98 (%)
A4	Arauca-Canaviche	Q0a	Riverside overflow	Undifferentiated	Partially very floodable 100%	18,5	26,8
B2	El Saman	Q0b	Deltaic alluvial plain	Banks 70%, bajío with banks 30%	Well drained 70% altogether very floodable 30%	28,9	33,4
C2	Guasdualito-Palmarito-Trinidad	Q1	Deltaic alluvial plain	Banks with bajío 75%, bajío 25%	Partially very floodable 75% altogether very floodable 25%	19,4	34,2
C3	Mantecal-Saman	Q1	Deltaic alluvial plain	Banks with bajío 75%, bajío with banks 25%	Totally floodable 75% altogether very floodable 25%	19,3	55,9
C4	Trinidad-Achaguas	Q1	Deltaic alluvial plain	Banks with bajío 70%, bajío with banks 30%	Partially floodable 70% totally floodable 30%	16,4	22,7
D2	Guasdualtico-Bruzual	Q2	Deltaic alluvial plain	Bajío 60%, banks with bajío 40%	Totally floodable 60% Partially floodable 40%	25,7	43,5
D3	Mantecal-Saman	Q2	Deltaic alluvial plain	Bajío 75%, banks 25%	Totally floodable 75% Partially floodable 25%	15,8	51,7
E1	Caicara-Setenta	Q3	Alluvial overflow plain locally covered with aeolian sediments	Flat with local undulations (loam) 75%, bajío with low banks (loam) 25%	Partially floodable 75% Partially very floodable 25%	26,4	59,3
F1	Orichuna-Balsa	Q1-Q2-3	Plain with loamy cover	Flat with local undulations and low dunes 65%, flat with waves 35%	Floodable	35,4	68,7
F2	Riecito Arauca	Q1-Q2-3	Plain with loamy cover	Flat with local undulations and low dunes 80% flat with waves 20%	Floodable	24,6	38,1

Map of the Modulo Hato El Frio (Figure 5) are a combination of all thematic maps and show the flood increase from the dry season to the wet season.

In the modulo area of hacienda Hato el Frio water is stored in a number of sinks. Upstream from the dike a larger sink is found. Downstream from the dike, sinks occur as well, but they are relatively small and do not cover a large continuous area. A detailed analysis of the flooding patterns of the modulo of the hacienda Hato el Frio is made by Smith *et al*. (2006).

The distribution of the flooded areas is strongly related to the formation of the study area as the geomorphologic processes determine the topography in natural landscapes and this, apart from soil characteristics, influences the patterns of flooding in the study area. The effect of the dikes is a recent phenomenon, which can clearly be observed in the flood maps (Smith *et al.* 2006). The other is the geomorphology of the area. In Figure 6 the main landscapes of the area are shown. The explanation of the legend is given in Table 2. The table shows the geological epoch, the relief, the geomorphology and the likelihood of inundation (ECOSA 1980). The percentage of inundation for

May and August 1998 for the different landscape unites is also given.

The comparison of the principal landscapes with the percentage of inundation shows a relationship between geomorphology and flooding. When comparing the landscape units with the percentage of flooded area, it can be observed that in August the flood extension is biggest in the flat zones (F1 and E1) partly because of the dikes. Dikes have a big impact in these flat sectors, as relatively small amounts of water flood large areas. Dikes can be most effective in those areas that are rather flat and can contain larger volumes of water. The landscape units that do not flood as much are the areas that were formed more recently (Q0 and Q1) and that have a higher percentage of banks (A4, B2, C2 and C4). Here relief makes it more difficult to construct dikes. The intermediate areas have a relative high percentage of bajíos. The relationship between dike system and flooding pattern for the modulo area of the hacienda Hato el Frio is explained by Smith *et al.* (2006).

DISCUSSION

The use of ERS SAR PRI images enables the studying of flooding dynamics, although the method also has problems. Dense vegetation coverage over the inundated areas makes the detection of flooded regions impossible. The formulation of classification rules is made difficult by the fact that the ecosystems in the area are natural or of little human intervention. The extremes between the dry and the wet season and also between the responses of the ecosystems to the changes make the vegetation development and mortality very heterogeneous. Nevertheless the comparison of the results of the image classifications with the inundation patterns and the principal landscapes show that an approximation is possible.

For the interpretation of the radar images, the different factors that influence the backscatter coefficient have to be taken into consideration. For ground surfaces, the magnitude of the backscattering coefficient depends on two factors: the dielectric constant of the ground surface and its roughness. The dielectric constant is highly influenced by the moisture content of the soil and less by its textual composition. If the vegetation is less than 10 cm high, it hardly has influence on the backscattering from the soil. Being higher, the influence of the vegetation depends on the macrostructure of the canopy, the height and the number of plants per area and its moisture content (Ulaby *et al.* 1996). In Le Toan *et al.* (1994) different examples of the effects of vegetation and soil moisture on the backscatter coefficient are shown. On bare soil, the backscatter values increase with the soil moisture, but for grass fields no correlation is found between the backscatter coefficient and the humidity of the soil (Wooding *et al.* 1992).

The influence of flooded surfaces on the backscatter is also highly correlated with the vegetation coverage. Inundation, soil moisture and dry biomass of grassy vegetation have different effects on the backscatter coefficient (Dobson *et al.* 1995). Vegetation growing on flooded surfaces has a large effect on the backscatter coefficient, even if it causes relatively small changes in the actual biomass. Escobar and Gonzalez Jiménez (1979) and Escobar and Medina (1977) studied the aerial biomass at Hato El Frio and found maximal aerial biomass of 676 g.m^{-2} in a bank with a vegetation community dominated by *Paspalum chaffanjonii, Axonopus purpusii* and *Sporobolus indicus*. In the bajío (hyperseasonal savanna) the maximum was 745 g.m^{-2} in a community dominated by *Panicum laxum, Paspalum chaffanjonii*, and *Leersia hexandra*. Within the semi-seasonal savanna the biomass was 857 g.m^{-2} in a community dominated by *Hymenachne amplexicaulis* and *Leersia hexandra*. Bulla (1980) studied the biomass in a modulo of Mantecal in the Llanos and found that the peak of aerial biomass in an estero was 1719 g.m $^{-2}$ and the in a banks 635 g.m $^{-2}$ (Sarmiento 1984).

In classification of the radar images of May 1998 some flooded areas could not be separated from the non-flooded areas. This was the case for areas, which had high vegetation coverage in May 1998, but were not flooded in May 1992. These areas do not enter the class "flooded" in any of the images, so the flooded area can be underestimated for all the images. These areas only occupy approximately 1% of the training area Modulo Hato El Frio.

In the radar image from December 1998, the flooded areas could only be distinguished in some sectors, as the vegetation was too high and dense in the majority of the region. The average vegetation coverage for the 23 sample points in December was 89 % compared to 72% of the 41 sample points in May 1998. The average height of the vegetation in May 1998 was 36 cm and 80 cm in December. For this reason no flood map was created for December, as the flooding would be underestimated.

The overall image of May 1992 has relatively high backscatter values when comparing to the other images. As no field data exists for this period and the climatic data from 1998 is not publicly available as yet, a comparison of the precipitation between the different years and the general interpretation of the image is difficult. Despite the uncertainties, it is assumed that the high backscatter values are derived from relatively low vegetation coverage combined with comparably high soil moisture contents. This is confirmed by field observations.

In the flood map, the increase of inundation from the dry to the wet season has been presented. At the end of the dry season (April 1988 or May 1992) very few areas are covered with water and in the wet season the approximately half of the area is inundated. When comparing the flooded area in April 88 for the entire area with the flooded area in May 92 for the northern part of the study area the difference is very small. This suggests that it is valid to the use the water areas of the classified Landsat image to show the flooding at the end of the dry season.

The areas of gallery forest were not classified in the radar images, but extracted from the classified Landsat image of April 1988. Also the flooded areas for the dry season for the entire study area were taken from this classification, as the radar image of May 1992 does not cover the whole area.

With the classification of radar images the inundation of any area can be monitored, but only the spatial extent is obtained with this method. The advantage of using radar images is that they cover a large area and are relatively cheap in comparison the field measurements; however, ground truth data are always required to check the validity of the radar interpretation and to allow ecological interpretation. .

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LITERATURE CITED

BULLA, L. 1980. Producción primaria, decomposición, flujo de energía y diversidad en un area del modulo experimental de Mantecal. Investigaciones en los Modulos de Apure. Informe final. Tomo I. San Fernando de Apure.

DOBSON, M.C., F.T. ULABY and L.E. PIERCE. 1995. Land-cover classification and estimation of terrain attributes using Synthetic Aperture Radar. Remote Sens. Environ. 51, pp. 199-214.

ECOSA 1980. Estudio Agrológico de Gran Vision: Estado Apure. Informe general, pp 241.Ministerio del Ambiente y de los Recursos Naturales Renovables, Caracas.

ESCOBAR, A. and E. GONZÁLEZ JIMÉNEZ. 1979. La production primaire de la sabane inondable d’Apure (Venezuela). Geo-Eco-Trop 3:53-70

ESCOBAR A. and E. MEDINA. 1977. Estudio de las sabanas inundables de Paspalum fasciculatum. In: IV Simp Int. Ecol. Trop., Panama, Resumenes, pp36-77. Panama. Int. Soc. of Tropical Ecology.

LAUR, H., P. BALE, P. MEADOWS, J. SANCHEZ, B. STATELIER, and E. LOPPING. 1998. ERS SAR calibration: derivation of the backscatter coefficient σ0in EAS ERS SAR PRI Products. Technical report, European Space Agency, Document No: ES-TN-RS-PM-HL09, Issue 2, Rev. 5b.

LE TOAN, T., P. SMACCHIA, J. SOUYRIS, A. BEAUDOIN, M. MERDAS, M. WOODING, and J. LICHTENEGER 1994. On the retrieval of soil moisture from ERS-1 SAR data. Proceedings Second ERS-1 Symposium, ESA SP-361, pp. 883-888.

SARMIENTO, G. 1983. The Savannas of Tropical America. In: Tropical Savannas, edited by F. Bourlière, pp 245-288.

SARMIENTO, G. 1984. The Ecology of Neotropical Savannas. Harvard University Press, Cambridge.

SARMIENTO, G. 1990. Las Sabanas Americanas: aspectos de su biogeografía, ecología y utilización. In: Ecología comparada de ecosistemas de Sabana en America del Sur, edited by G. Sarmiento pp 15-56. Fondo Editorial Acta Cientifica Venezolana, Mérida.

SARMIENTO, G. and M. PINILLOS. 2000. A conceptual model relating ecological constraints to livestock production in tropical American seasonal savannas. In: Consequences of Land use change, edited by Ü Mander and R.H.G. Jongman, WITpress, Advances in Ecological Sciences 5, pp 295-314.

SARMIENTO, G. and M. PINILLOS. 2001. Patterns and processes in a seasonally flooded tropical plain: the Apure Llanos, Venezuela. J. of Biogeography

28 (8): 985-996.

SILVA, J.F. and A. MORENO. 1993. Land use in Venezuela. In: The world's savannas: economic driving forces, ecological constraints and policy options for sustainable land use, edited by M.D. Young,.D. & O.T. Solbrig, UNESCO MAB series; vol.12, pp. 239-258. Paris

SMITH, J.K., E.J. CHACÓN-MORENO, R.H.G. JONGMAN, PH.. WENTING and J.H. LOEDEMAN. 2006. Effect of Dike construction on water dynamics in the flooding savannah of Venezuela. Earth Surface Processes and Landforms 31:81-96

ULABY, F.T., P. C. DUBOIS and J. VAN ZYL. 1996. Radar mapping of surface soil moisture. Journal of Hydrology 184, pp. 57-84.

VIVAS, L. 1992. El Cuaternario. Universidad de Los Andes, Mérida.

WOODING, M.G., G.H. GRIFFTH, R. EVANS, D. KENWARD, and G.E. KEYTE. 1992. Temporal monitoring of soil moisture using ESR-1 SAR data. Proc. of First ERS-1 Symposium 641-647 Cannes, France.

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