Use of G.I.S. and Remote Sensing in Hydrological Model for Impact Study of Land Cover Change in a Malagasy Rural Basin

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ABSTRACT

A conceptual distributed-based model has been developed for flood simulation and forecasting. The model structure consists of a square grid network, in analogy with the raster form of numerical maps. The square-pixel is the analysis unit for hydrologic balance in relation with physical characteristics. Punctual and cartographical data sources are used to characterize each mesh. Aerial photography and satellite imagery give information about land use. Topographical characteristics are obtained from Digital Terrain Model (DTM). Soil type can be numerized to help in estimating the drainage condition. Hydrological data are distributed in accordance with the Thiessen's polygons or the associated sub-basin. All the data are handled by the GIS part in order to classify the surface runoff potential of all meshes. This procedure allow to consider the physical characteristics and the spatial variability of the parameters at small scale, to manage special devices like storm basins, pumping stations and spillways and to do a quick study of the spatio-temporal evolution of the characteristics. Impact analysis of land cover modifications on the river flow regime is therefore possible. In one large rural Malagasy watershed, since the 1960's, several waterworks were achieved in order to struggle against the flooding of the upstream fertile plain (subject of various developments). Meanwhile, the forest of the basin hillslopes was and still strongly claimed for pluvial rice crop, which is necessary for the subsistence of a fast growing population. The main object of this work is to study the hydrological impacts of these changes of land use on the watershed behaviour and to forecast the basin water regime evolution.

INTRODUCTION

Each modification of the physical characteristic of the basin implies a change of the hydrological river regime. The use of a regionalized hydrological model is very useful for the prediction of the impact of land cover changes on the volume of the runoff and its transfer. These models allow to predict the flow regime of the rivers even those non-equipped with measuring instruments. They require a good description of the phenomena and the hydrological parameters linked to the watershed physical characteristics. The spatial distribution of the physiographical and hydrological characteristics can be identified either from remote sensing data or from numerical cartography in general. Several models are developed and proposed for the optimal use of the numerical cartography in hydrological modelling (Abbott and al., 1986; Allewijn, 1990; Schultz, 1988; Walsh and Gregory, 1985; etc.).

The hydrological simulation model and flooding prediction in a basin, developed in our laboratory, is now adapted to study different problems associated with the environment. The model is based on a meshed basin, considering the meshes of the discretized basin as the analysis unit. The hydrological balance, which is a function of the physical characteristics, is computed for each mesh. This allows to take into account both the spatial variability of these parameters on a small scale and the quick study of the characteristics spatio-temporal evolution and particularly the impact analysis of their changes on the river flow regime. The modification of the environment, and especially of the forest, is a subject of world-wide interest, mainly in developing tropical countries. This is the case for the eastern part of Madagascar where the clear-cutting and clean-burning for temporary pluvial rice crops are not simply traditional customs but become vital for the subsistence of a fast growing population due to the immigration and exploding demography. Though, these cultivation methods are not necessarily beneficial and may cause harmful consequences which are difficult to evaluate at the moment. It will be interesting to study the impact of the basin physical characteristics changes, particularly of the land cover, on the river flow regime in the watershed.

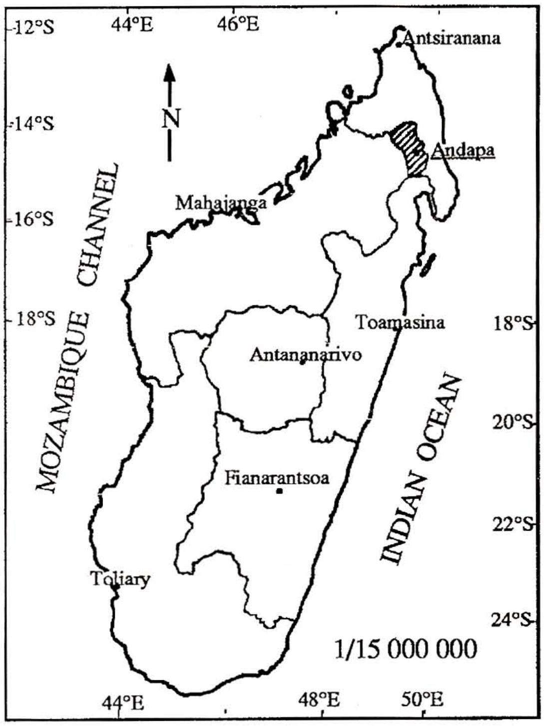


Fig. 1 - Geographical location of Lokoho basin.

The present paper concerns the case of a large Malagasy basin where the land use is continuously modified both due to several developments in this watershed and the deforestation preceding temporary pluvial rice crops on the hillslopes.

1. BASIN DESCRIPTION

The watershed of *the Lokoho* river is located in the North-East part of Madagascar [Figure 1]. It covers approximately 1050 km^2. The main town in the area, called *Andapa*, is situated at the latitude 14°40' South and at longitude 49°40' East. The relief is characterized by the marked contrast of two geomorphological units clearly differentiated. The center of the basin is occupied by a large plain at the altitude included between 460 and 500 meters surrounded by mountainous chains with abrupt hillslopes (>20%) whose tops fluctuate between 1200 and 2400 meters.

These two entities are separated by an intermediate foothill zone with medium slope (10-20%). The *Lokoho* 's basin is named the *Andapa bowl* due to its bowl-form relief with high edges where the unique aperture is a small outlet between two hillbottoms [Figure 2]. The flooding of this fertile plain is due to the incapacity of its aperture to evacuate rapidly the runoff concentration coming from the surrounding hillslopes.

Since the 1960's, that plain has been the center of interest for many developments projects. Financial support has been given by the FED (*Fond Européen pour le Developpement*: European Development Fund) to exploit the agriculture in the *Andapa* plain. Several waterworks were achieved in order to fight against frequent plain flooding causing damage to the cultures, the breeding, the habitat and the inhabitants too. These works consist in the widening, the deepening, the weed-cutting and the correction of the *Lokoho* watercourse in the zone of the aperture. Technically, the aim was to obtain a critical flow regime in order to evacuate intense flows with low water levels.

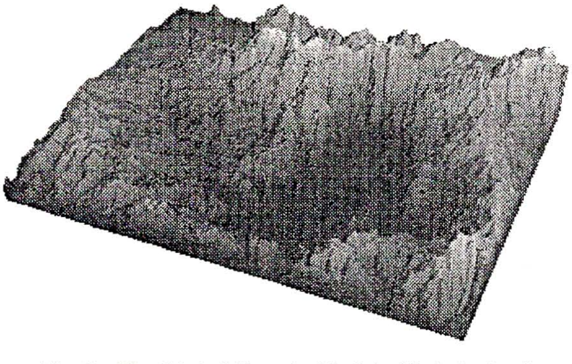


Fig. 2 - The Digital Terrain Model of Lokoho basin.

These allowed to reduce the passing water height during the heavy flooding and consequently to reduce the upstream plain flooding risk. Different another developments of the plain have been also executed like: *-detour and embankment of the rivers; -drainage and transformation of the hydromorphous parts of the plain into rice fields; -development and rehabilitation of tracks and bridges; installation of energetic power station, pumping stations; -several micro-hydraulic dams and some gravitational irrigation network for the irrigated rice perimeters during dry periods; -training, variety research and popularization for rice, coffee and vanilla cultivation* (Agrer, 1978).

The bowl is characterized by a humid and warm tropical climate. The mean temperature varies from 18°C in July to 25°C in February which is the warmest month. The relative moisture is approximately of 87% but can reach 97% in March and April. The annual rainfall is of about 2041 mm spread over 271 days whose 65% falls from December until March. This period is characterized by the passage of cyclones remarkably fearsome for the water level rise. The cyclonic storms are characterized by intensive rainfall during a short period often associated with violent winds which can exceed 9 m/s. In 1966, a rainfall of 104 mm was recorded in one night during the cyclone named *Collette*. During the *Georgette* cyclone in 1968, 228.4 mm felt in 24 hours and 202.5 mm in 24 hours during the *Danae* cyclone in 1976 (Agrer, 1978).

In the flooding period, the mean *Lokoho*'s flow is approximately of 100 m3/s but can reach 2000 m3/s during the cyclone heavy showers. A 8 meters waterwall associated with a flow of the last magnitude mentioned has been observed at the outlet during the *Georgette* cyclone. The completed waterworks of the 1960's were able to evacuate such flow with 6 meters water height instead of 8 meters as observed during the *Danae* cyclone in 1976.

From the geological point of view, the largest part of the area is covered by old soils belonging to the metamorphic Precambrian age located in the gneiss of the graphite system interrupted in the North and South by granites with Malgachitic facies (*charnockites*) having some dispersed quartzite outcrops. A ferralitic alteration cover occupies the gneiss hillslopes whereas the bottom of the hills and the plain are respectively constituted by silty-stony and silty-clayey soils, sometimes hydromorphous clayey soils (Agrer, 1978).

The hillslopes were entirely colonized by dense forest vegetation with scattered coffee and vanilla crops. However during the last 30 years, temporary pluvial rice crops interrupt the dense forest stratum monotony. Before planting the pluvial rice crops, the terrain is cleared and fired. After rice cultivation the piece of land is generally left fallow. These cultural practice are typical to the region and are commonly called *Tavy system* for temporary pluvial rice crops and *Savoka* for fallow land. On the other hand, the plain having bad drainage conditions is almost entirely transformed in rice fields.

These modifications of vegetation in the basin are principally due to the human activity mainly oriented towards agriculture. The inhabitants are characterized by their various origins, by their recent occupation of the territory and by their quick increase after an exploding demography and immigration caused by the land fertility and the promising developments. The population density spread over 765 km^2 is of 93 inhabitants per km^2 with a growing rate of 4%.

For the subsistence and the well-being of such growing population, the land cover of the basin underwent a lot of changes with perhaps some catastrophic consequences. The subject of this study is particularly oriented on the follow up of these land cover changes by aerial photography treatment and remote sensing and the evaluation of their impacts on the flow regime of the river.

2. THE FOLLOW UP OF LAND COVER EVOLUTION

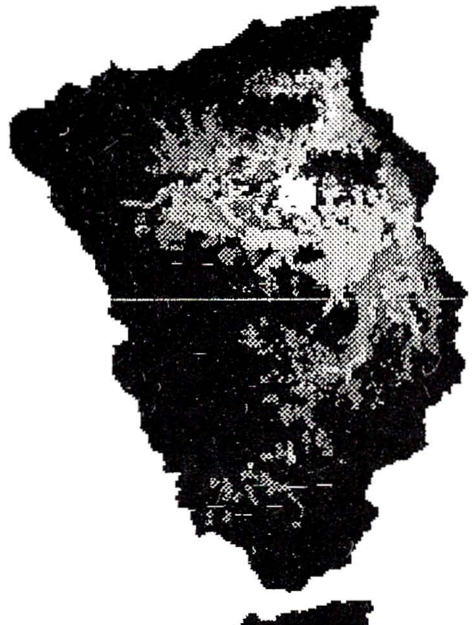
Three different situations of the *Lokoho* basin land use were mapped. The first two state maps presenting the vegetation cover were obtained from the restitution of aerial photographs taken respectively in 1957 and 1978. These maps are numerized by using the ARC/INFO software and are represented firstly under a vectorial form and later on, transformed under a raster form in order to be in conformity with the Digital Terrain Model (DTM). The third situation of the vegetation cover is immediately obtained under a raster form after the treatment of two SPOT multispectral scenes using the I^2S software. Each numerical map has a final spatial resolution of 100 meters which is a compromise between a sufficiently good homogeneity representation of the various land cover types and a reasonable file size for an optimum computing time on the Macintosh computer workstation. The quantitative evaluation of each land cover type, in other words their surfacing, becomes an elementary task because it is represented simply by the pixels counting of each type.

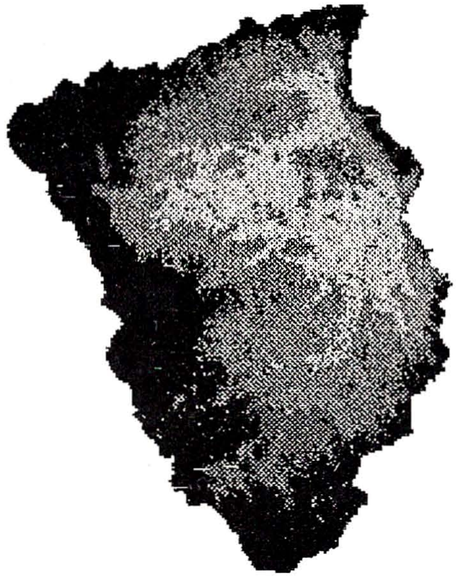
2.1 Situation in 1957 [Figure 3 a]

The restitution of aerial photographs, taken in 1957, on cartographic documents has been published in 1963 (scale 1/50 000 and 1/100 000) by the National Geographic Institute of Paris. These maps give information of the land cover before the realization of the first development into the watershed. Seven land cover types were itemized: primary forest (800 km^2, 77.8% of basin area), pluvial rice crops after clearing and firering and bushy fallows following the temporary pluvial rice crops (72.33 km^2, 6.92%), coffee and vanilla crops (55.77 km^2, 5.33%), habitation (3.81 km^2), ponded rice fields (39.78 km^2) and marshy areas (60.42 km^2) [Table 1]. These pictures clearly demonstrate the real rural character of the watershed. Like in this situation, the human activity on land cover before the recent developments was very low. The number of inhabitants was less than 50 000 for the total area.

2.2 Situation in 1978 [Figure 3 b]

The restitution of the aerial photographs taken in the end of 1977 and the beginning of 1978 by BETT-AEROMAP gives a cartographic background (scale 1/50 000) of the land cover in the *Lokoho* basin at that period. Both view and restitution are used in a project of protection against deforestation and erosion in the watershed which became of great concern. Globally, the same soil occupancies as in 1957 are recognized with the difference that eroded areas were observed. The new class of eroded soils is spread over the watershed and covered about 14.96 km^2 (1.43%) [Table 1]. At that moment, the forest represents only 48.72% of the basin or 509.32 km^2. On the other hand, the complex *Tavy-Savoka* is spread over 326.42 km^2 (32.22%) while the coffee and vanilla crops occupy more than 7% of the watershed or 74.61 km^2. The importance of the habitat increased but stays relatively low (0.85%).





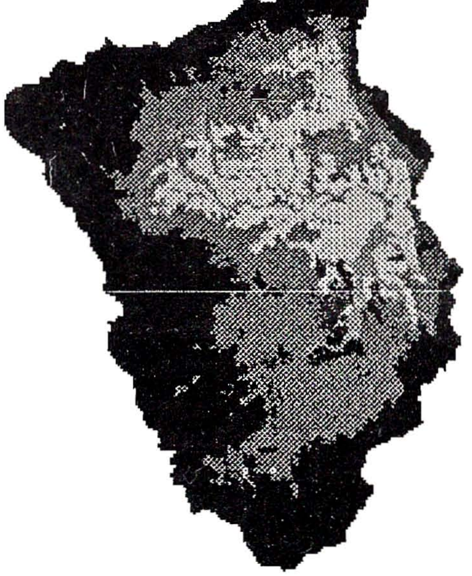


Fig. 3 - Land cover a) in 1957 b) in 1978 c) in 1990.

After the development of the plain, all the marshy areas were converted into irrigated rice fields totalling 111.31 km^2 (10.65%).

The situation in 1978 is marked by deep modifications of the major part of the land cover. Indeed, several steps of the hydro-agricultural development of the plain were already achieved and the deforestation of foothill were nearly generalized. Both the national and international authorities and the backer became preoccupied by the deforestation problem. Watershed protection became a new objective in the bowl development project.

Table 1: Land cover evolution in the *Lokoho* basin for three situations (* *Complex Tavy - Savoka system*).

	1957		1978		1990		1957-1978		1978-1990	
	Surf. (ha) (1)	% (2)	Surf. (ha) (3)	% (4)	Surf. (ha) (5)	% (6)	Surf. (ha) (7)=(3)-(1)	% (8)=(4)-(2)	Surf. (ha) (9)=(5)-(3)	(10) % =(6)-(4)
Forest	81336	77,80	50932	48,72	57627	55,12	- 30404	- 22,68	6695	6,4
Fallow *	7233	6,92	32642	31,22	21040	20,12	25409	24,3	- 11602	- 11,1
Crops	5577	5,33	7461	7,14	14422	13,79	1884	1,81	6961	6,65
Habitation	381	0,36	885	0,85	1405	1,34	504	0,49	520	0,49
Rice	3978	2,80	11131	10,65	8321	7,96	7153	7,85	- 2810	- 2,69
Marshy	6042	5,77			1732	1,66	- 6042	- 5,77	1732	1,66
Eroded			1496	1,43			-	-		

2.3 Situation in 1990 [Figure 3 c]

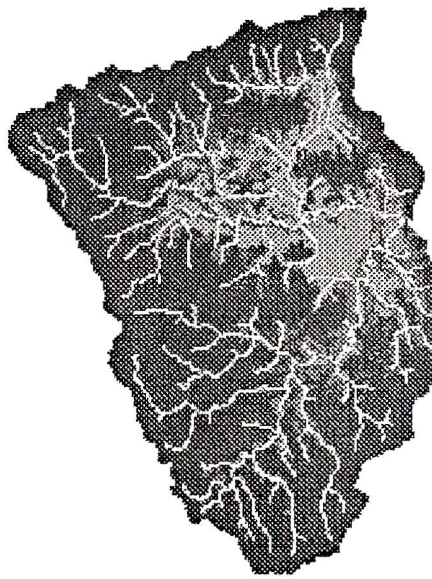
In the project for the watershed protection, the actual situation was necessary in order to have a global view on the vegetation cover evolution on the hillslopes. Two multispectral SPOT scenes, covering the entire basin, were treated. Only a few scenes were available because the region is often cloudy. SPOT scenes taken at two different moments (7/3/90 for KJ171-379 and 16/2/89 for KJ171-380) were used. No other LANDSAT-TM scene was available. The histogram of the reflectance frequencies of the region presents a remarkably Normal distribution.

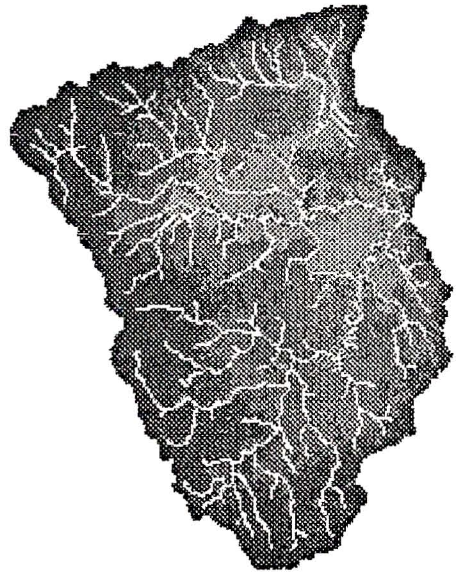
The first stage of the treatment consists in the contrast improvement allowing easily the selection of the training areas necessary for the initialisation of the classification algorithm. The two scenes were classified by the maximum likelihood estimation method in eight classes: primary forest, secondary artificial vegetation, secondary natural vegetation, coffee and vanilla crops, rice-fields, habitation and roads, rivers and water ponds and non-classified area. The terrain knowledge and a series of aerial photographs were used for the choice of the training areas during classification. Then a geometric rectification of the map and mosaicing are done. The use of an original post-classification treatment algorithm permits to homogenize the classification and to correct by substitution some affectations which were judged badly classified (Binard and Colette, 1992). The numerization of the watershed boundary and other vectorial elements facilitates the localization of roads and leaks and allows the mask creation for the elimination of areas outside of the basin. The file with the roads and leaks was corrected interactively by superposition of the vectorial elements on the redressed coloured composition. The classification file is systematically sounded in order to obtain the information with a resolution of 100 meters to be realistic on a treatment point of view in the hydrologic model and in order to be conformed with the DTM. The resulting classification is printed as a map with all marginal information at the scale of 1/100 000.

The non-classified zone (2.7% of the basin) was corrected referring to the situation of 1978. The quantitative result can be summarized as following. The forest totals 567.27 km^2 (55% of the basin). The distinction between the areas under complex *Tavy-Savoka system* (210.4 km^2) and the zones with coffee and vanilla crops (144.22 km^2) was not clear because they are almost mixed all over the basin. A same problem is encountered with the rice fields (83.21 km^2) and the ponded areas (17.32 km^2) [Table 1]. These confusion can be explained by the low contrast of reflectance due to the development of the vegetation during the rain period where the bushes foliage becomes relatively dense and when the rice fields are ponded.

2.4 Comparison and evolution [Figure 4 and figure 5]

The standardization of the classification is necessary to allow a serious comparison of the three situations and to deduce the land cover evolution. Indeed, the three cartographic documents were created independently by three different operators and different methods. In this study, vegetation is only considered by its hydrological role in the basin, notably for the rainfall interception, the evapotranspiration, the overland flow and the infiltration. Some land cover type can be gathered together in a same vegetation class according to the height, the density and the flow control potentiality. Four vegetation classes are finally retained [Figure 4 a,b,c]. The first one is the high-sized vegetation class gathering together the primary and the secondary forests. The second type is the medium-sized vegetation class, constituted by the coffee and vanilla crops, the *Tavy*, the *Savoka* and the habitation. The habitation area is included in this category because in the major case they are built up with leaves and trunks of the raffia, the bamboo or other trees and generally surrounded by coffee, vanilla or banana crops. In any case, it represents only a small part of the basin due to the rural character of the basin. Effectively there are only few concrete buildings in the commercial center of *Andapa*. No other ubanization substructure is present and the villages are connected by tracks. The third class, represented by the small-sized vegetation, groups the ponded rice fields and the marshy areas of the plain. The last class is constituted by the rivers (class without vegetation).





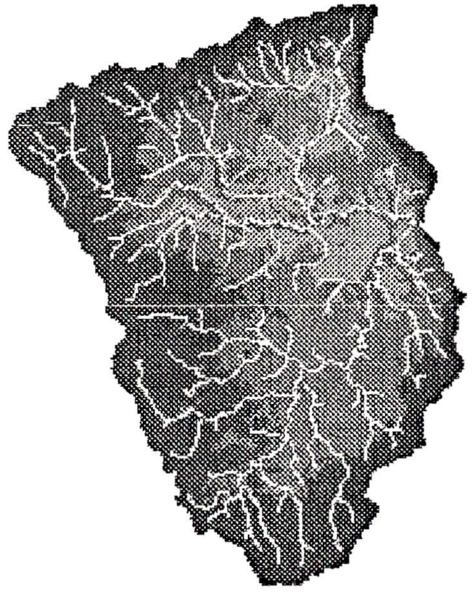


Fig. 4 - Vegetation classes a) in 1957, b) in 1978 and c) in 1990.

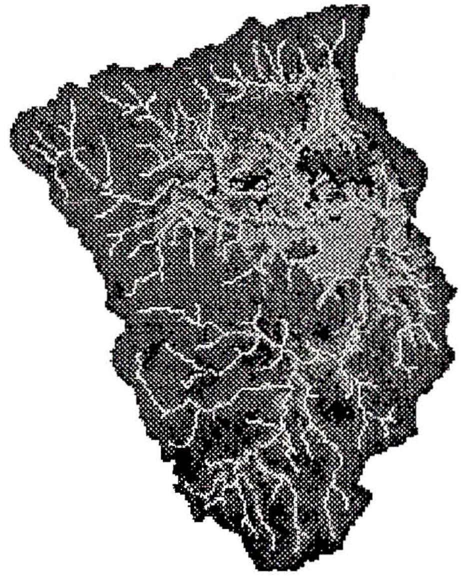
The heaviest human activity to the detriment of the forest is observed in 1978. Then 37% of the forest in 1957 are destroyed. The affected zone is spread over 304 km^2 or 22.68% of the basin area. The felled forests were essentially replaced by temporary pluvial rice crops *Tavy* with fallows *Savoka* whose occupied surface was propagated on 24.3% of the surface basin (254 km^2) [Table 1].

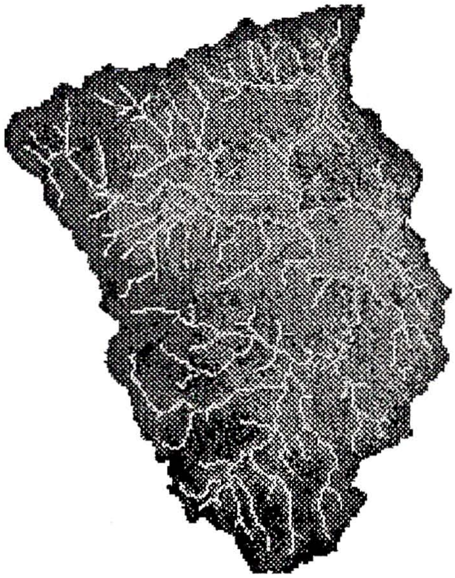
To add a qualitative aspect to the analysis of the three situations, the vegetation classes were combined with a topographic characteristic of the basin. The considered parameter is the slope calculated from the DTM in accordance with the highest slope's line for each mesh which is a function of the altitude of the eight nearest neighbours. The punctual slope values were classified into three categories, respectively the low, medium and steep or *"high"* slope (0-10%, 10-20% and 20%). They are well spread all over the basin and represent respectively 37.37%, 25.46% and 37.17%.

The different vegetation classes agree perfectly with the three geomorphological entities distinguishable by the chosen slope classes. The high-sized vegetation generally appears on the abrupt hillslopes while the medium-sized vegetation in zones with medium and low slopes (like the plateau on the mountain's top and the foothills between the plain and the hillslopes) and the small-sized vegetation in the plain [Table 2 and Figure 5].

Indeed, the combination of the land cover and the slope class shows that the major part of the forest (near of 50%) is located on the abrupt hillslopes (which represent respectively 35.18%, 25%, 25.45% of the basin for the three situations). Only 20% of the forested part is located on the top plateau and in the plain and about 30% on the foothills with intermediate slopes.

Though the deforestation between 1957 and 1978 affected all the forest classes over areas having sensibly the same surface *i.e.*: respectively 91.38 km^2 on low slopes, 93.91 km^2 on medium slopes and 106.41 km^2 on steep slopes [Column 4 of the table 2]. A clear deforestation preference is observed for areas with low and medium slopes, probably because of the easier access and especially for taking advantage of the rainfall because the crops are not irrigated. Indeed, the forest on low slopes in 1978 decreased more than 50% in comparison with the situation of 1957. The forest on medium slopes decreased only about 40% and those on steep slopes less than 29% [Column 5 of the table 2].





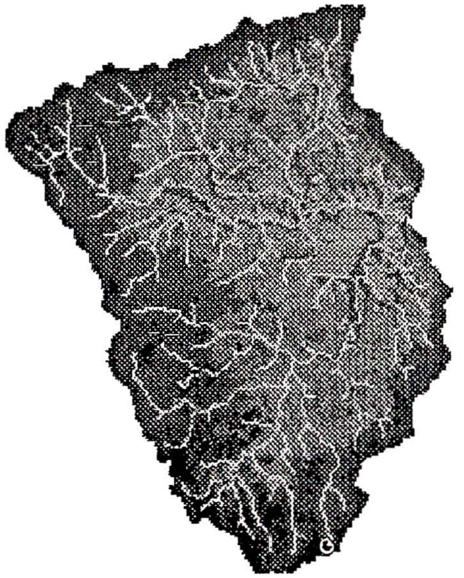


Fig. 5 - Hydrological class a) of 1957 situation b) of 1978 situation c) of 1990 situation.

Between 1978 and 1990, the regeneration and the reconstitution of the high-sized vegetation seem to be favourable because it increased in 65.95 km^2. This reconstitution concerns essentially the forest on low slopes with increasing of 44.33% in comparison with the situation of 1978, whereas the vegetation on medium and steep slopes increased respectively of 12.85% and 1.79% . This is due to the vegetation development conditions more favourable on low hillslopes and the more intensive erosion which slow down the vegetation regeneration on steep slopes. In 1990, the regeneration of forest cut between 1957 and 1978 correspond respectively to 43.73% on low slopes area, 32.52% on medium slopes and 4.41% on steep slopes. The final balance between 1957 and 1990 shows a decrease of about 30% of the three high-sized vegetation categories. The medium-sized vegetation class presents an inverse evolution of the forest because deforestation is thanks to the development of the former one.

Concerning the small-sized vegetation, almost the total of the plain is developed in rice fields in 1978 contrary to the situation of 1957 where 30% of the area (60.42 km^2) represented marshes. It is also probably the case in 1990 where the distinguished ponded areas during the treatment of the satellite remotely sensed data represent the swamped rice shootbedding of the plain rice fields (case in February).

However, the forest areas in 1990, can be overestimated because of the low reflectance difference between forest and bushy fallows. But the local conditions are really favourable to the quick development of the vegetation and the abandoned fallows can be transformed into a secondary forest (Randriamaherisoa, 1991). It is interesting to take profit of these conditions to elaborate agroforestry solutions for the fixation and the clever modification of the human activities in the deforested areas in accordance with a suitable soil conservation program with the protection of some natural reserves.

Table 2: Relative importance and evolution analysis of hydrological classes in the *Lokoho* basin.

CLASS	1957 Surf. Ha (1)	1978 Surf. Ha (2)	1990 Surf. Ha (3)	1957-78 Surf. Ha (4)=(2)-(1)	1957-78 % (5)= 100(4)/(1)	1978-90 Surf. Ha (6)=(3)-(2)	1978-90 % (7)= 100(6)/(2)	1957-90 Surf. Ha (8)=(4)+(6)	1957-90 % (9)= 100(6)/(4)	1957-90 % (10)= 100(8)/(1)
HiVg LoSlp	18151 17,36 %	9013 8,62 %	13009 12,44 %	- 9138	- 50,34	3996	44,33	-5142	43,73	- 28,32
HiVg MeSlp	23602 22,58 %	14211 13,59 %	16037 15,34 %	- 9391	- 39,79	1826	12,85	-7565	32,52	- 32,05
HiVg HiSlp	36776 35,18 %	26135 25 %	26604 25,45 %	- 10641	- 28,93	469	1,79	-10172	4,41	27,66
MeVg LoSlp	8073 7,72 %	16336 15,63 %	13142 12,57 %	8263	102,35	- 3194	- 19,55	5069	38,65	62,79
MeVg MeSlp	2110 2,02 %	11394 10,90 %	9761 9,34 %	9284	440	- 2731	- 23,97	6553	29,42	310,57
MeVg HiSlp	1900 1,82 %	12492 11,95 %	12039 11,52 %	10592	557,47	- 453	- 3,62	10139	4,28	533,63
LoVg LoSlp	9040 8,65 %	9915 9,48 %	9113 8,72 %	875	9,67	- 802	- 8,09	73	91,65	0,81
LoVg MeSlp	294 0,28 %	401 0,38 %	208 0,20 %	107	36,39	- 193	- 48,13	-86	80,37	19,25
LoVg HiSlp	79 0,08 %	128 0,12 %	112 0,11 %	49	63,02	- 16	- 12,5	33	32,65	41,77
River LoSlp	3809 3,64 %	3809 3,64 %	3809 3,64 %	-	-	-	-	-	-	-
River MeSlp	609 0,58 %	609 0,58 %	609 0,58 %	-	-	-	-	-	-	-
River HiSlp	104 0,10 %	104 0,10 %	104 0,10 %	-	-	-	-	-	-	-

Label codification: Hi *for High,* Me *for Medium,* Lo *for Low,* Vg *for Vegetation and* Slp *for Slope*

3 THE MESHED HYDROLOGICAL MODEL AND THE USE OF GIS AND REMOTE SENSING

3.1 Description of the meshed hydrological model

Actually, the hydrologists are oriented towards mathematical modelling because of the uncertainties of the results calculated with empirical methods. Two models can be distinguished. The first one is the stochastic model where the mathematician is looking for some relation between a rainfall input and a flow output. This model gives good results on large watersheds where the parameters managing the rainfall-flow relation are relatively stable. But it needs many observations spread over many years. On the other hand, the deterministic models, more physical based, try to represent the rainfall-flow relation by simulating the different phenomena included in the flood generation. This second model is the best adapted to study the influence of one or an other phenomena on the relation by changing the parameters linked to the physical aspects of the phenomena.

The proposed meshed hydrological model is a deterministic model of *the distributed conceptual type*. It is used for the flood discharge simulation and particularly for the forecasting of design flood. It is constituted by two functions. The former concerns the production function modelling the way by which the rainfall is transformed on overland flow. This function is governed by the runoff coefficients depending on the rainfall intensity, on the soil canopy, on the soil slope and on soil type. The second is the transfer function which treats the way by which the overland flow reaches the watershed outlet. It is governed by a runoff speed depending on the slope, the aspect and the soil canopy or channel characteristics. These runoff speeds are used to calculate the isochrones which are the lines of equal transfer time to the outlet. The combination of these two well-described phenomena leads to a methodological approach of the rainfall-flow relation called *the isochrone method*. The originality of the square-grid model is the discretization of the watershed in a series of meshes which are the analysis units where these functions are considered. The advantage of the model is the possibility to take into account the hydrological parameters on a small scale and consequently their the spatial variability in order to treat differently all the possibilities. From this point of view, it follows that an urbanized zone located near or far upstream in the watershed can cause different responses at the outlet of the basin. The existence of a pumping station or a storm basin modifies the river regime downstream. A more advanced application of the square grid model consists in the evaluation of the spatio-temporal evolution impact of these parameters considering different situations during several periods. It is the case of the land cover changes due to urbanization, deforestation and other developments.

3.2 The use of remote sensing and GIS in the meshed model

The good integration of the numerical cartography and satellite imagery in the meshed model allows to take into account both the physical characteristics of the basin and the study of their spatio-temporal evolution in the hydrological modelling [Figure 6]. Until now, the tedious parametrization work is the great disadvantage of the model. Indeed, it needs the definition mesh per mesh of all physical characteristics used in the model. This represents a long and boring work and limits the use of the isochrones method for didactic exercises.

Though, the two physical aspects taken into account in the model, *i.e. the land cover and the land topography* are now available under a computerized form with the aid of remote sensing and the Digital Terrain Model (DTM). These two information were used to automate the parametrical stage of the model, formerly manually executed. The actual evolution of the computer sciences favours these considerations because of the repetitive character and the computerized facilities of the parametrization.

The digitalization of the documents stem from the restitution of aerial photographs and the treatment of the satellite imagery gives numerically the qualitative and quantitative information on the land cover. The physical characteristics of the watershed relief intervening in the model, *i.e. the slope, the aspect, the crest lines, the thalwegs, the natural drainage network, the automated basin and sub basin delineation* are inferred from the DTM. The latter is ela-

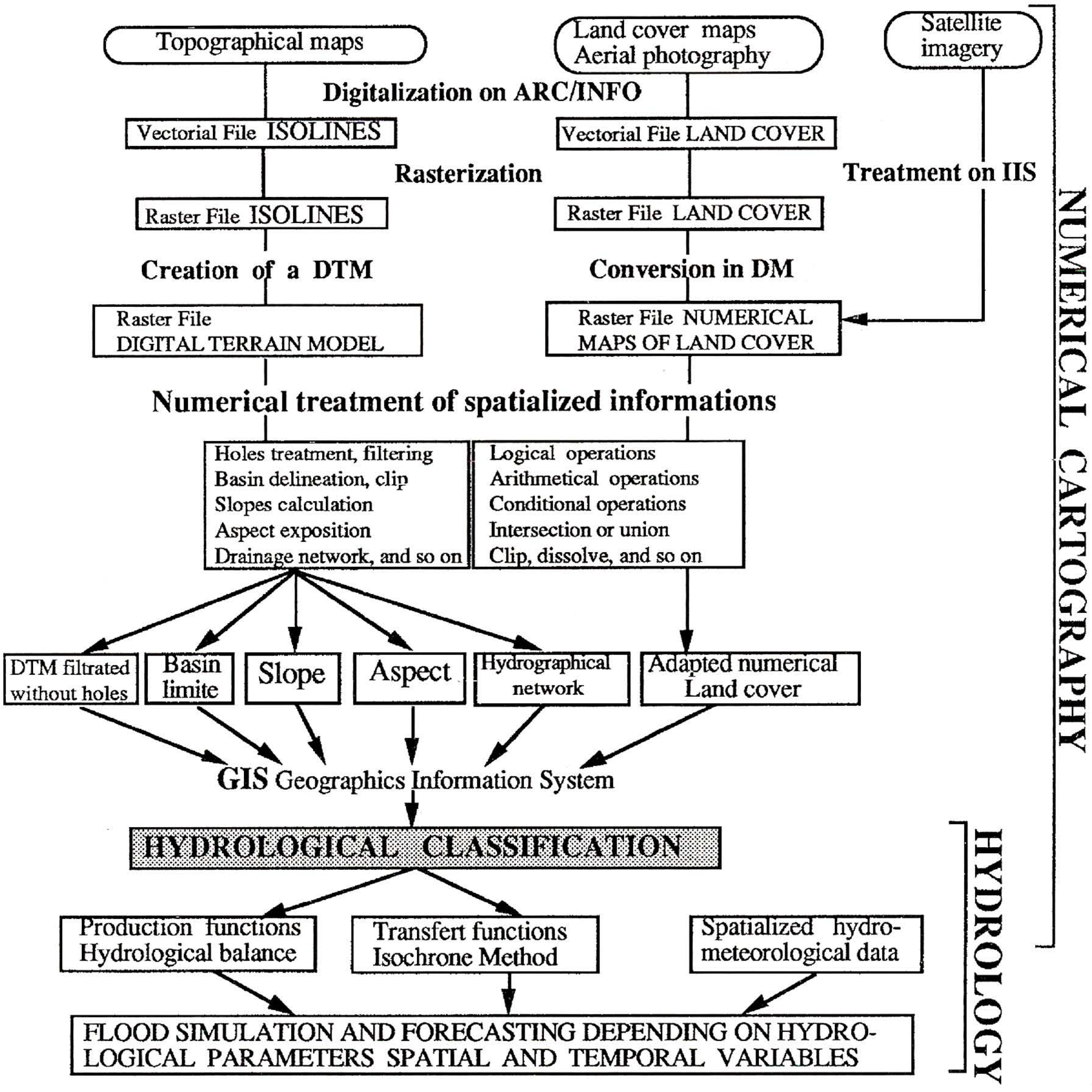


Fig. 6 - Implementation organigram of the model.

borated from treatment of the vectorial numerical map issued from the contour lines digitalization of the topographic map on ARC/INFO software. The interpolation of the altitude of each grid network node is done in accordance with the highest slope line with special treatments for crest lines and thalwegs. The artificial holes and the eventually aberrations are corrected to permit drainage.

The implementation organigram summarized in the figure 6 shows the importance of the numerical cartography and particularly the remote sensing in the model. The treatments of the satellite images and the digitalized base documents gave different numerical maps of the topography and the soil canopy necessary for the model. These maps are the inputs of a raster type GIS intended for the hydrologic classification of the basin meshes and for the distinction of special cases like collecting basins, pumping stations that need particular considerations [Figure 5 a,b,c and Table 2].

The GIS output is the input of the production and the transfer functions of the model. The spatial distribution of the meteorological and hydrometrical data is taken into account in the model by raster numerical maps that represent the influence areas of each station installed in the basin. These influence zones are determined either by the Thiessen's polygon method or with the associated sub basins. Each mesh receives the meteorological data from the nearest station or the corresponding sub basin. The parameters fitting is a preliminary stage necessary to the use of the model for the peak discharge simulation or the design flood forecasting linked to particular rainfall of given intensities, duration and frequencies.

The information management is sometimes significant and the simultaneous fitting of several parameters is not easy because some bad combinations give the same result. The good sense, the operator experience and the physical phenomena interpretation fill the lack. The fitted parameters importation from other similar basins or the use of standard values allows the by passing of the fitting step and permits to go straight to the flood simulation and forecasting.

4. APPLICATION AND CONCLUSION

Until now, there are few studies on the influence of the physical characteristics changes on the basin hydrological regime. The difficulty appears when it is necessary to introduce the spatial variability and the dynamic characteristics of the environment in the hydrological model. Moreover, the limited availability and the non-representativeness of punctual measures constitute a crucial problem in hydrological modelling. Indeed, a measurement point is expensive especially if the data are useful for different successive time intervals. The transposition of the punctual data in the effective hydrological properties spatially distributed is a difficult task. Only the deterministic distributed models using a physical base are the best adapted to treat this kind of study.

The earlier presented procedure is used for the study of the deforestation impact on the *Lokoho* hydrological regime. The runoff potentialities expressed by the runoff coefficient and the runoff speed for each combination land cover-slope class are fitted with the data of 1990. Indeed, the suitable meteorological and hydrometrical data are only available since 1989. The adjusted parameters are used for the hydrological regime simulation of the earlier situations. The meshed basin and the spatial distribution of the parameters according to the combination land cover-slope class permitted to modify the values of the meshes subjected to changes, without modifying the other ones. A same rainfall storm is used for the simulation of the flood hydrograph relative to the three situations of the *Lokoho* land cover. This application shows that the concentration time of the basin (the time required for rain falling at the farthest point of the basin to flow to the outlet) was of about 12 hours in 1957 and decreased by 2 or 3 hours in 1978. This decreasing is linked to the flow acceleration due to the reduction of the rainfall interception and to the removal of the buffering role of 304 km^2 cut forest between the two situations.

After the runoff acceleration and due to the supremacy of the meshes having higher runoff coefficient, the peak discharge pertaining to the same rainfall period increased of about 10 % to 15%. On the other hand, between 1978 and 1990, after the stabilization and the improvement of the situation due to the regeneration of the high-sized vegetation, the net rainfall volume for the overland flow is less important. The maximum flow for the same rainfall period decreased of 2%. Moreover, the transfer of the net rainfall is slowed down and the basin concentration time increased about 30 minutes. The hydrological regime of a river is modified upstream with the physical and hydrological characteristics changes. That are the consequences of the deforestation in the *Lokoho* watershed. During the flood period with a saturated soil condition, the *Lokoho* peak flow is inversely proportional to the surface of the high-sized vegetation (forest) in the basin. On the other hand, the concentration time has the same evolution as the forest surface. How more important the forest surface is, the longer the time of concentration will be and slower is the overland flow in the basin. This is due to the physical phenomena linked to the presence of the forest. The more important the rainfall interception and evapotranspiration are, the less important the runoff is.

Due to the deforestation, the runoff concentration in the plain may become higher again and the peak flow will favour the flooding of the well-equipped fertile plain and destroy the efforts of the last 30 years to struggle against the flooding in the *Lokoho* basin. Decisions must be taken in order to find the compromise between the land use for the subsistence of a fast growing population and the forest and soil conservation. Agroforestry solutions seem to be the most favourable by giving to the inhabitants the agricultural production techniques combined with the high-sized vegetation. The local conditions seem to be ready for this kind of solution.

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