Natural Resource Management using Integrated Modelling : The Case of the Niger River Inland Delta

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Abstract The Niger River inland delta in Mali covers 30 000 km^2 and hosts 1 million inhabitants, who are traditionally exploiting its natural resources (fisheries, livestock, agriculture). Different attempts to model the functioning of this ecosystem were undertaken by formulating various hypotheses on the availability of water (droughts, construction of dams), the regeneration of natural resources and their exploitation. Modelling results of SIMDELTA, based on cognitive agents exploiting a biotope with a number of appropriate techniques, relate to the impact of fishing on the fish stock, showing that the yield reaches a maximum value, which is maintained despite an increasing fishing effort due to the resilience of the stock. A second model, Midin, was developed in a later stage, covering the entire delta, representing the flood pulse, the regeneration of the natural resources and the different farming systems. The farming systems are represented through a labour market model with reactive agents. The modelling results show the importance of the annual flood pulse and the spatial fragmentation of the delta, and the existing equilibrium in the exploitation of the natural resources of the delta. The projected construction of river works and extension of irrigation schemes will thus have a tremendous impact on the natural resources. The results of the modelling can be used at a global and local level. At a global level, modelling can be used to evaluate the impact of interventions on the ecosystem and farming systems, and to anticipate potential conflicts over the use of resources. At a local level, the process of decentralisation underway in Mali provides opportunities for the management of natural resources.

Keywords: Humid zones; Modelling; Hydrology; Natural Resource Management; Mali

1. INTRODUCTION

1.1 The Niger River Inland Delta in Mali

In ecosystems like the Niger River inland delta, the hydrological regime, the dynamics of the natural resources and human activities (fisheries, agriculture, livestock) are closely associated. The sustainability of the exploitation of natural resources of such an ecosystem is crucial. How to ensure the transition from the current situation of intensification of the exploitation towards a management of the natural resources in the economic development process of the delta?

The Niger River inland delta covers an area of about 35 000 km^2 from Ké-Macina and San in the south to Timbuktu in the north (see Figure 1).

One million people inhabit the delta, a tenth of Mali's population. It covers an area of about 30,000 km^2, and produces one tenth of the country's rural GDP. Every year, an area of about 10,000 to 20,000 km^2 is inundated. The ecosystem as well as the traditional farming systems that exploit its natural resources in the flood plains and lakes (fisheries, agriculture, livestock) depend on the extent of the annual river floods [Gallais, 1984]. The delta is frequented by an estimated 2 million cattle, and as many sheep and goats. Farmers cultivate an area ranging from 50,000 to 130,000 ha of deep-water rice with yields below 1 ton/ha. The annual fish catches are over a 100,000 tons during wet years.

Just upstream of the delta a large-scale 60,000 ha irrigation scheme diverts annually about 10 % of the Niger supplies. Currently, there are a number of projects underway to extend the irrigated area. A master plan of this irrigation scheme envisages ultimately an irrigation infrastructure for over 250.000 ha. In addition, the governments of Guinea and Mali are planning the construction of a series of dams on the upstream catchment for the generation of hydropower or the development of irrigation. Since the regeneration of natural resources depends directly on the extent of the flooding, any extension of the irrigation schemes upstream of the delta or the installation of dams will have an impact on the ecosystem and thus on the traditional farming systems.

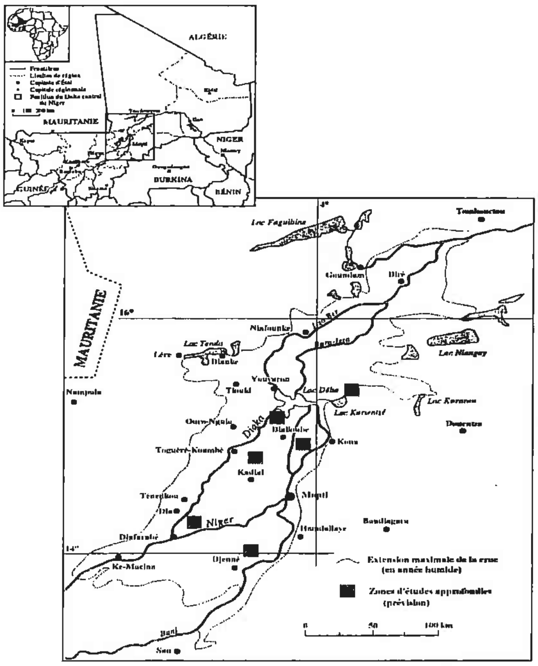


Figure 1. Location map of the inland delta of the Niger river in Mali.

A research programme was carried out in order to understand the dynamics of the natural resources, and to assess the sustainability of the farming systems. One of its aims was to contribute to the acceptance of the delta as a management unit, while anticipating its future evolution. The research questions being:

- How will this ecosystem be transformed under population pressure, increasing pressure on land and access to resources, technological advances, impact of hydraulic works (dams), current administrative decentralisation policy?
- How to make more tangible the multiple uses of water in this river basin, including the needs for conserving this unique ecosystem, identified in the RAMSAR Convention, in order to take better decisions on water resources development.

Two aspects are taken into account: 1) the long term dynamics of the physical, biological systems, 2) the needs and the multiple uses of the populations concerned.

1.2 Modelling of Natural Resource Management

Modelling is used here to combine the dynamics of the natural resources and a socio-economic approach of human activities. The objectives of the modelling were at the same time the description of the system, the analysis and the understanding of its functioning, and the simulation of its evolution.

Modelling experiences in the ecosystem of the Niger River inland delta started with the work on SIMDELTA, an agent-based model developed in the early nineties [Bousquet et al., 1993], focused on the study of the regeneration of fish and the impact of fishing activities on the fish resource. The ecosystem was represented through a small number of "technotopes", i.e. different combinations of biotopes and fishing equipment. The modelling effort was focused on understanding the resilience of the fish resource.

In the late nineties, the integrated modelling of the Niger River inland delta, formalised through the Midin model, was undertaken to integrate other farming systems (agriculture, livestock) and to represent the delta as a whole to understand the dynamics of the regeneration of the natural resources, to evaluate their (traditional) exploitation, and to assess the sustainability of these farming systems [Kuper et al., 2000]. The resulting model is referred to as Midin.

The aim of this paper is to assess the approach used in terms of the representation of the different processes and their interactions, and the results that are obtained in the simulations in the light of an integrated management of natural resources.

2. PRESENTATION OF THE MODEL

When defining the software implementation of Midin, a modular configuration was respected with thematic modules, each representing a different process. This has resulted in a multi-layer architecture, allowing a dynamic representation for each process. Object oriented programming principles have proved to be very practical for the implementation of a multi-layer system.

The user interface represents the main features of the model: its spatial structure with mapping, its dynamics with animation of different entities, and its functional structure by allowing direct manipulation of the control parameters. The model can perform a comparison of simulation results of two different values of a given control parameter. It can perform a global sensitivity analysis based on 10 different values of a control parameter.

The model is accessible via internet: http://www.orleans.ird.fr/midin/ and can be executed in any Java compatible environment.

2.1 Scales

A common extension and a common spatial scale for all processes have been selected, and the dynamics of the system have been represented in this framework, while considering the evolution of representative spatial entities. The spatial extension of the model is the maximum inundated area of the delta from San to Timbuktu (Figure 1).

The entities represented are the hydrological units (flood plains, lakes and rivers), groups of fishermen, groups of farmers, herds of bovines, and the production zones of the different farming systems (fisheries, agriculture and herding).

The model runs during three hydrological years, from May to April: '93/'94, '94/'95 and '95/'96. These years represent a dry, wet and average year in terms of rainfall and extension of the whole-inundated area. The time step used by the model is a 15-day period.

2.2 Hydrological, Spatial and Social Entities

Three types of spatial entities have been defined [Kuper et al., 2000]: (1) rivers and channels conveying water, schematised by straight lines ("segments"), (2) connections, contact points ("nodes") where rivers and channels diverge or converge and (3) flood plains and lakes, where water is stored temporarily or permanently, schematised by cones. The hydrosystem is thus represented by segments, cones and nodes. The representation has yielded a total of 109 objects: 7 lakes, 12 flood plains, and 90 segments (Figure 2). These objects determine the structure of data and the definition of the mechanisms that feed the model. The occurrence of water intervenes in all the different processes and in all entities, which makes it the main explicative variable.

The following spatial entities have been identified: farming zones, fishery zones and pastoral zones., all linked to an hydrological object. The selected spatial entities have been geo-referenced and have a hydrological sense, conveying and stocking water. They have a socio-economic sense, since they correspond to the representation of the local communities of the different exploitation zones. The inland delta as a natural system is limited by its outer perimeter of fluvial inundation, but is functionally defined as an oriented, open network.

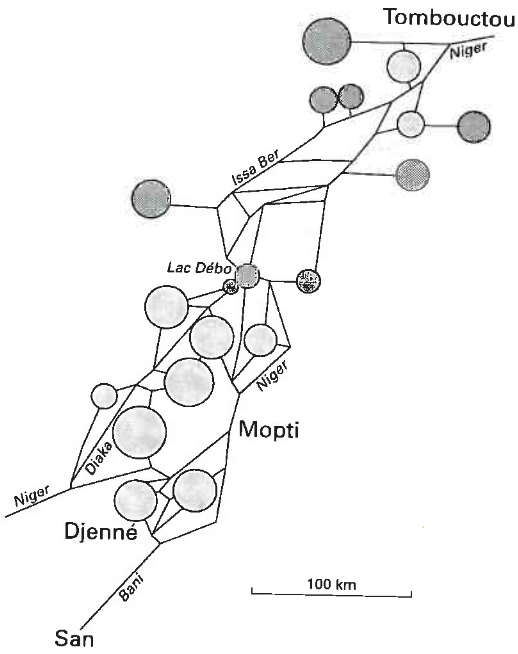


Figure 2. Hydrological entities: lakes, flood plains, rivers and channels, connections.

The other entities represented in the model are groups of peasants (fishermen, farmers), and herds of cattle, which are linked to their zone of origin, but who have also access to other zones (principle of mobility). These social entities are reactive agents, obeying to a "labour market" formalism, described in the farming systems module. The access to the different zones is subject to traditional rights and regulations [*e.g.* Gallais, 1984], for example through family ties (principle of connectivity). Cattle herds are considered as entities in the process of production, just like rice farmers and fishermen.

2.3 A behavioural Model

Individuals, whose spatial behaviour can be considered homogeneous [Gallais, 1984] are represented in groups. The model represents groups of people, residing in a village with a specific behaviour in terms of exploitation and migration. Behaviour is not based on "rational choices", but on social rules and patterns. The hypothesis is that the spatial behaviour of agents is structured and that in the short term, this structure does not change, and can be quantified and modelled. This is one of the reasons for adopting a maximum timeframe of three years for the simulations. Beyond that, the hypothesis is untenable since the changes in external environment would lead to modification of social patterns and behaviour.

2.4 Modules

The *hydrology module* is a reservoir model, where cones represent the flood plains and the lakes. It suffices to calculate the radius at time t, which is a function of the water level and the geometry of the object (bed level, maximum water depth, minimum and maximum radius) to calculate the inundated area. In this module, it is possible to simulate the effect of climatic conditions and the construction of river works (barrages, dams) on the river floods by changing the control parameters.

The *fish resources* module is based on Bousquet et al. [1993], and represents the temporal and spatial dynamics of the generation and dispersion of fish populations.

The *farming systems* module is based on a "labour market" model. The fishing and agricultural activities are represented through a "pulling" model. Groups of fishermen, farmers can move to production zones whenever there are opportunities to exploit the natural resources. Moving to a production zone is possible when a particular group has traditional links with the zone. Whether or not a group moves depends on the availability of natural resources, the opportunities of exploitation, and the inundation of the area. Livestock activities are represented by a "pushing" model. Herds of cattle move in the delta following traditional tracks, penetrating in pastoral zones based on traditional access rights [Gallais, 1984]. The cattle herds go from one zone to another based on the hydrological season, and on the grazing capacity: the zones "push out" the herds when they are saturated.

3. RESULTS OF SIMULATION

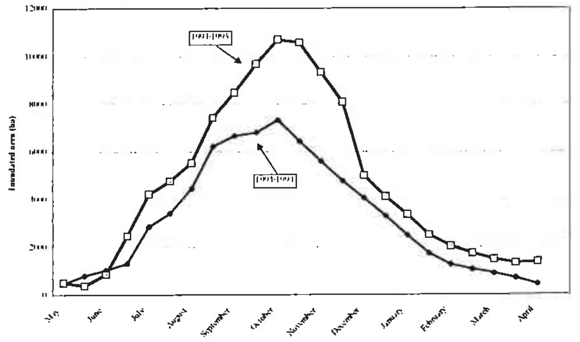
3.1 Representation of the System

The spatial interface of the models has provided a good means to reconstitute the complexity of the system while understanding the significance of each of the elements (objects, processes). The model describes the hydrographic entities of the ecosystem with their respective characteristics (size, depth, location...), and the different connections. Thus, three important aspects of the functioning of the ecosystem are represented:

- The ecosystem as a whole at a regional scale, with the corresponding hydrological processes (storing of water, flows).
- The local level, represented through its 109 geographic entities, each with its own identity and precise description in a hydrological and socio-economic sense.
- The mobility of the resources (water, land, fish, pasture) and the consumers/transformers of these resources is particularly emphasised.

3.2 Analysis and Understanding of the System

The reaction of the natural resources to the pressure exerted by fishermen was studied by Bousquet et al. [1993]. Several simulations were conducted with SIMDELTA, dealing with the increase of pressure (drought, demography, technological improvement) on the resources. The most interesting result is the identification of a plateau effect. After an initial increase, the level of fish catches remain stable for a long time although fishing pressure increases: the exogenous mortality is balanced by the ecological production. It was further observed that the application of social rules (leading to heterogeneous access to the biotopes and the heterogeneous use of technologies) lead to a better state of the resource than the model of economic rationality, based on individual maximization of the expected benefits.



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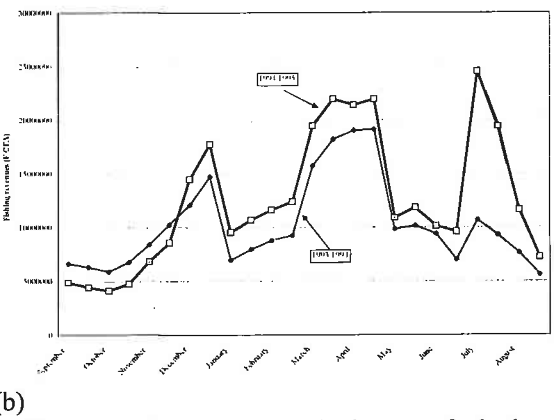


(b)

Figure 3. Comparison of the impact of a bad ('93/'94) and good ('94/'95) hydrological year on the fishing revenues, example of the lower Diaka flood plain.

The hypothesis that water is crucial to the natural resources in this ecosystem, was confirmed by several studies. Kodio et al. [2000] show, for instance, an almost linear relationship between the flood pulse and fish production. Similarly, the location and extent of the rice production depends directly on the flood pulse.

To understand the impact of the flood pulse in the different flood plains on the farming systems, a simulation was carried out with Midin to compare a bad (1993/1994) and good (1994/1995) hydrological year (Figure 3). The figure shows the relatively small extent of the inundated area during bad hydrological conditions (Figure 3a), resulting in a lower production of natural resources. The different peasant groups will be directly affected. The revenues of fishermen (Figure 3b) for instance are the same in the beginning of the year, but decline sharply thereafter when fishermen have exhausted the fish resources.

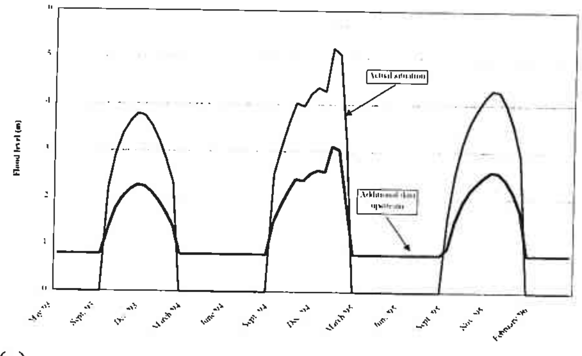
3.3 Evolution of the System

The construction of a series of dams is actually under consideration in the Niger River basin to generate hydro-power or to provide water for irrigation. However, the impact on the natural river flows is crucial for the regeneration of the natural resources of the delta as well as the prosperity of its traditional farming systems.

Bousquet et al. [1993] showed, using SIMDELTA, that the catches at time t are dependent mostly on the previous year perturbation. Bad environmental events and strong fishing efforts are smoothed quickly. It was shown that this very resilient dynamics is mainly due to the annual hydrological pattern and the spatial fragmentation of the ecosystem. Modifying the flood pulse pattern or reducing the heterogeneity of landscape and heterogeneity of access to the resource will lead to a decrease in the adaptive capacity of the ecosystem to respond quickly and efficiently to various kinds of pressure.

The impact of a dam upstream of the delta on the floods, the natural resources and the farming systems is illustrated in Figure 4 through a simulation, using Midin, for the Koli Koli River in the north of the delta, assuming the construction of a dam with a reservoir capacity of 10 billion m^3.

Figure 4a shows the croping of the flood level and the increase of the water level in the dry season due to the dam regulation, thus reducing considerably the inundated area in the flood plains. The traditional rice cultivation is directly hit, showing a decrease in the cultivated area, a decrease in the number of families cultivating rice, and a decrease in the farm revenues. The attenuation of the floods decreases the availability of fish during the year and a decrease in the revenues of fishermen is observed in Figure 4b.



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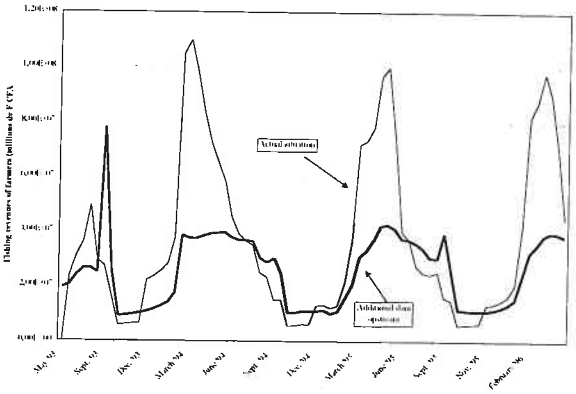

(b)

Figure 4. Simulation of the impact of a dam upstream of the delta with a reservoir capacity of 10 billion m^3, example of the Koli Koli River.

4. TOWARDS THE INTEGRATED MANAGEMENT OF NATURAL RESOURCES

4.1 Understanding the Functioning of the Ecosystem

An increased understanding of the functioning of a complex system can contribute to a better management of natural resources. Research in the Niger River inland delta showed, for example, the resilience of the fish stock to traditional fishing activities of fishermen and the almost linear dependence of the fish production on the extent of the floods [Kodio et al., 2000]. While management efforts were hitherto focused on the preservation of fish stocks by introducing a system of permits, the research results show clearly that it is more important to conserve the ecosystem by maintaining the natural floods of the Niger River.

4.2 Local and Global Outputs

Depending on the questions, integrated modelling can be targeted to provide information at different scales. In the case of the Niger River inland delta, an effort was made to provide both global information on the ecosystem as well as iat the level of a single flood plain.

At the global level, the information was intended to recognise the ecosystem as one management unit and to evaluate the impact of policy and management interventions on the farming systems and on the environment. This corresponds to the concept of integrated river basin management, applied for example in France through the river basin authorities [Barraqué, 1998].

The simulation results show how the different farming systems depend on the extent of the inundated area. The modelling work can help to study the interactions between these farming systems under the influence of the hydro-climatic conditions (*cf.* the Sahelian droughts of the 1980s). This is important due to increasing competition for space and resources and resulting conflicts in the Sahel [Gallais, 1984]. The analysis and prognosis of economic, social or even political unbalances, due to a heterogeneous impact on the different farming communities (in space, in time), can help to anticipate problems in the availability of natural resources and identify interventions to address these problems.

Providing information at the level of a flood plain or a rural municipality may contribute towards providing actors with information to help manage natural resources, especially in the context of decentralisation efforts underway in Mali. This was not explored in this case so far, but experiences in Senegal, where the farming communities were actually involved in developing a model for the management of agricultural and pastoral lands, show the interest of such an approach [d'Aquino, 2001].

5. CONCLUSION

A first conclusion of the modelling work concerns the importance of the flood pulse and the heterogeneity of the landscape for the regeneration of the natural resources of the Niger River inland delta. Current projects of expanding irrigation schemes upstream of the delta, and constructing dams for the generation of hydropower should be examined in the light of their potential impact on the delta.

The different hydrological and socio-economic entities of the delta (channels, lakes, flood plains) have been spatially represented in order to account for their key role in the production of natural resources, through their hydrological and geo-morphological characteristics. By modelling these entities as dynamic objects, reacting to the flood pulse, the regeneration and exploitation of natural resources are better represented. The spatial heterogeneity and annual variability in the availability of natural resources, explains the mobility of peasants, reacting to opportunities provided by the ecosystem.

The social rules governing the farming systems, exploiting the natural resources, are shown to be favourable to the reconstitution of these resources. Interventions targeted to preserve the ecosystem and favour the economic development of its inhabitants, should be based on the understanding of the existing delicate equilibrium between natural resources and those exploiting them.

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