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# Management of a Tropical River: Impacts on the Resilience of the Senegal River Estuary

Coura Kane, Alioune Kane, and Joël Humbert

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## Abstract

Tropical rivers are under constant pressure and are subjected to flood control policy and planning. The Senegal River has been, for more than thirty years, under multiple types of management and planning. That has become recently more important because of significant hydro-climatic variability that has occurred during recent years. Higher levels of winter rainfall have resulted in frequent occurrence of flooding which guided Senegalese authorities to create an artificial opening on the sand of spit so-called Langue de Barbarie. The major consequence of this has been the closing of the old mouth of the Senegal estuary 25 km downstream of the town of Saint-Louis. However, two new mouths have opened themselves recently within 150 m of the current mouth. The increasing vulnerability in the Senegal River estuary has been one of the main impacts of the watershed management of the Senegalese northern River accordingly. The developments of Senegal River management policy have been based on the concept of remedying the consequences of climatic events; then, the utilization of water resources presented risks that are far greater than expected.

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## Keywords

Watershed management • Resilience • Risk • Estuary • Senegal River

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## Introduction

Due to rapid growth of the population and lack of resources in developing countries, people tend to settle along coastal areas and develop activities in estuaries which receive

constant natural and anthropogenic actions. Human beings have not been insensitive to the wide array of opportunities provided by the coasts and have been attracted to them, making the coasts the most favored locations to either live permanently, for leisure, recreational activities or tourism (Martinez et al. 2007; Culliton et al. 1990; Miller and Hadley 2005). Thus, Senegal River estuary has undergone significant alterations as a consequence of the hydrodynamic conditions that have prevailed there following human actions established in the area. With the construction of the Diama and Manantali Dams, in addition to the new opening on the mouth of the “Langue de Barbarie,” the Senegal River has experienced major changes due to many water planning decisions (Kane et al. 2013). These decisions were made in the context of significant hydro-climatic variability. This resulted in the constant hydrological deficit recorded

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during the 1970s, but also exploited the higher levels of rainfall, particularly prevalent during those years.

The Senegal River estuary is an extremely fragile environment; it is threatened by natural hazards such as the recurrent floods. This situation stems from the physical environmental conditions. The risk is thus permanent, which can be exacerbated by human presence and its multiple actions on the environment. By interventions was generally failed to seriously predict the effects induced, and they frequently destabilized environments characterized by precarious equilibriums. The new mouth of the Senegal River is causing significant damage to the estuary. This arrangement does not fail to change the hydrological regime of the estuary and especially led to changes in estuarine ecosystems and increased the vulnerability of the estuary. Anthropogenic actions lead, most often, uncertainty of the occurrence of catastrophic events. In this context, the domino effect can be triggered, resulting in, as a result, increasing vulnerability. The impacts associated with climate change will be much more catastrophic in Africa because of the weakness of the economy and the rapid growth of the coastal population (Nicholls and Cazenave 2010). Climate change and rising of sea levels will increase the risks to which the estuary of the Senegal River is already exposed, whereas the system has low capacity to absorb disturbance.

Enhancing disaster risk reduction before a disaster occurs, and also during the reconstruction process, requires enhanced knowledge regarding the most vulnerable groups, the areas at risk, and the driving forces that influence and generate vulnerability and risk (Birkmann 2007; Bogardi and Birkmann 2004). Better take into account of the physical environment in policy development is essential. Environmental assessment aims to contribute to environmental awareness among proponents and competent authorities and to environmental protection by requiring the ex ante evaluation of the environmental impacts of a wide range of public and private initiatives such as spatial plans (Runhaar et al. 2013). The vulnerability of the Senegal River estuary area was accentuated by the water management of the Senegal River with the opening of the new mouth that was made without prior impact assessment. To a certain extent, the resilience of the system is strongly found to disturb. For this reason, it is essential to carry out detailed studies of the impacts of development on the hydrological regime of the river and the consequences in the upstream and downstream portions. All positive and negative impacts should be considered before making a layout and fairly weigh the consequences of choices.

In this chapter, the consequences of the watershed management of Senegal River in the estuarine area are analyzed. This last appears as a space where a variety of risk factors which may cause significant damage. Its occupation makes these areas vulnerable for local riparian. The

latter has a low capacity of resilience from watershed management issues.

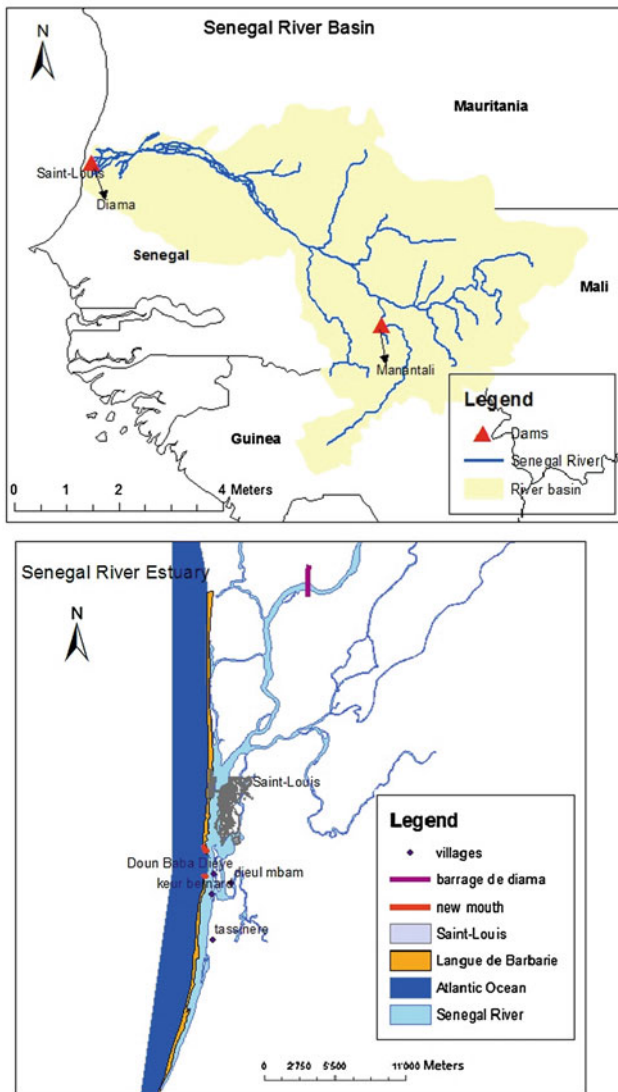
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## Human Pressures and Functioning of the Senegal River Estuary

The presence of a risk linked to existence water resources in an area determines the way the population exploit it; that situation influences strongly the type of structure and management settled consequently (Beucher and Rode 2009). The situation of the Senegal River obeys to this concept. Somehow, it could be promoted some existing geo-engineering technologies when used properly have low or no significant negative impacts (Olson 2012).

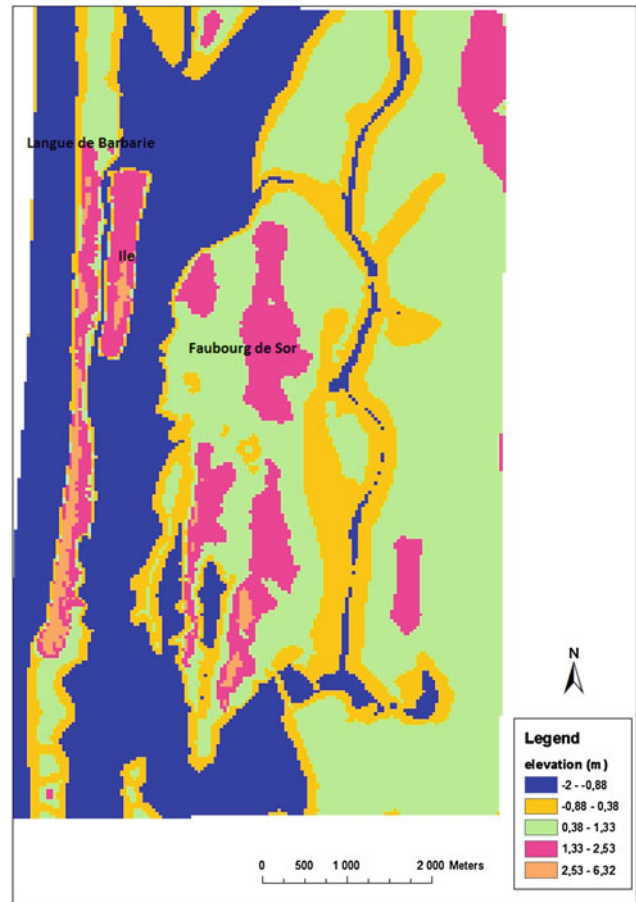
Climatic variability is determining factors in risk management. In the 1970s, the Sahel region experienced a period of exceptional water deficit in terms of duration and intensity. This period of rainfall decreasing is still on going (Dai et al. 2004; L'Hôte et al. 2002, 2003) although less strong since the mid 1990s than during the 1980s. The average rainfall over the last 37 years has remained below the 1900–1970 average in this region with large-scale consequences (Hulme et al. 2005). For almost all rivers of West Africa has decreased (Mahé and Paturol 2009). More than 125,000 people died in the African French-speaking countries during this period, in addition to the successive food shortages of the 1972–1974 period (Dauphine 2003). A loss of 600,000 tonnes of the grain crops was also recorded, equivalent to about a 15 % reduction in average annual income. In livestock farming and during the same period of 1970s, there was an 80 % cattle loss (Guillaumie et al. 2005). As a consequence, the survival of the socio-ecological system was endangered, in addition to being subject to severe risks that resulted in destructive disasters. Water control appeared to be essential for reducing the system's vulnerability. Thus, the “taming” of nature became a significant challenge for riparian states and the construction of the Diama and Manantali dams on the Senegal River (Fig. 1) was the solution adopted to ensure sustainable development and food security.

The Diama Dam resulted in considerable modification of the hydrological regime of the Senegal River downstream of the structure. Freshwaters are stored in the upstream of the dam. They arrived in the estuary during the rainy season (Saint-Louis station), when dam gates are opened and when they are some releases from Diama Dam. In addition, the principle of functioning of the Diama dam is to close it in periods of low water to prevent the intrusion of saltwater and to open in period of floods to allow floodwaters to flow downstream (OMVS 2003). The role of the Diama Dam in controlling the Senegal River is strengthened by the Manantali Dam.



**Fig. 1** Location of the Senegal River basin and estuary

The Sahelian zone has in recent years recorded a return of heavy rainy seasons. In the tropical wet area of Guinea, high basin River, we note abundant precipitation creating an increase in the river water flow. The increase in the river water levels generates overflows which further increase the risks of floods. The town of Saint-Louis stuck between the Senegal River and Atlantic Ocean (Fig. 1) is built on an area dominated by deposits of mud and is particularized by the omnipresence of water (Kane et al. 2013). The digital elevation model (Fig. 2) shows the lower elevations of the city of Saint-Louis and identifies the most sensitive areas to flooding. Low areas represent 53 % of which 17 % have altitudes between  $-1$  and  $0$  m and 36 % emerging barely above sea level is between  $0$  and  $3$  m. They correspond, in fact, the main bed of the river is located in “Faubourg de Sor.” The slopes are also very low; they are between  $0$  and  $9$  %. In “Faubourg de Sor,” the slopes are practically nil and they vary between  $0$

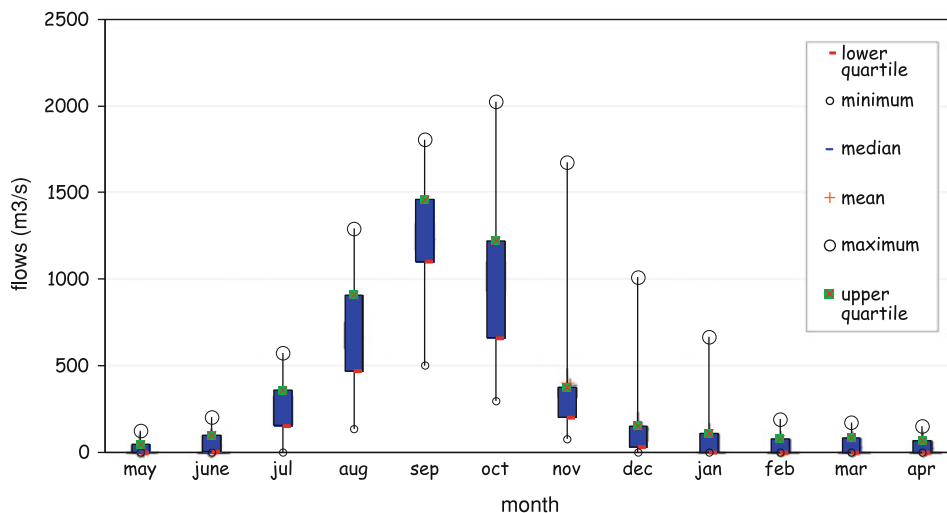


**Fig. 2** Digital elevation model Saint-Louis

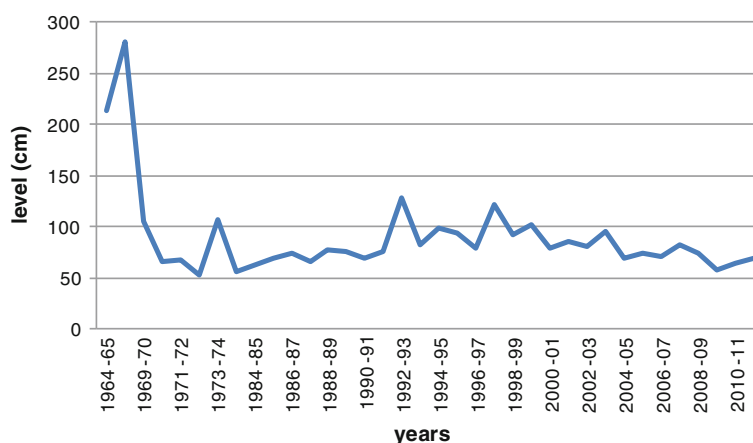
and 2 %. Also, at this point, changes in the water level will be low in case of flooding and lead to greater variation in the extent of water. Many cities are located in flood areas as they are likely to be places favorable for urban development (Tingsanchali 2012). The town of Saint-Louis is in a similar situation to many others throughout the world, for example, in Ethiopia where floods occur regularly in all parts of the country at times of rising water levels downstream of large basins and in low ground (Ayalew 2009). In Saint-Louis, following many years of drought, the local population occupied much of the river bed normally under water; consequently, many districts may be flooded in the event of a major rise in water level. This raises the important issue of population relocation during rainy seasons, as it is also a limitation to the smooth flow of people and goods. This weakening of the socio-economic system in the face of the threats of flooding prompted the Senegalese authorities to open a new mouth on the “Langue de Barbarie” in 2003 to enable a rapid escape of excess water toward the sea.

Thus, since July 1986, the Diama Dam has controlled most of the water influx into the estuary. An average annual of  $255 \text{ m}^3/\text{s}$  is released into the river below the dam during this period. Water flows through the dam since 1986

**Fig. 3** Senegal River flows at Diamo dam station (1986–2010) (OMVS Data) Organisation pour la Mise en Valeur du Fleuve Sénégal: Organization for the Development of the Senegal River



**Fig. 4** Changes in water level at the Saint-Louis Station (1964–2012) (Data source: Division Régionale de l'Hydraulique de Saint-Louis/ Ministère de l'Hydraulique et de l'Assainissement)



(Fig. 3) enable determination of the estuary's monthly and annual flows, showing two periods:

- a 4-month period (August to November) during which the estuary is invaded by flooding water and
- a 8-month period during which the estuary is subject to marine influence.

The dam's highest water flow is in October. The highest flows are in August, September, October, and November, and the lowest usually in December, January, February, March, May, April, June, and July.

In order to ensure that instructions on the dam's proper management are followed, occasional releases can be carried out by managers to guarantee its safety. The openings of floodgates are related to the support of raising water levels at the Manantali dam, which at certain times requires substantial water releases to be taken from reserves intended for other needs, while higher than turbine output (Bader 1997). Moreover, with the operation of the hydroelectric station at the Manantali Dam since 2002, the floodgates of the Diamo Dam are regularly opened to avoid overflow of the river banks.

Figure 4 shows changes in water level at the Saint-Louis station from May 1964 to April 2012, showing a succession of peaks which reflects the strong inter-annual variability of the flow. Water flows have reduced since the 1970s with a clear decline in water level, from a peak of 281 cm in 1965–1966 to an average of 54 cm in 1972–1973 reflecting changes in the climatic conditions in the Senegal River basin. Although insignificant, the river's water level seems to have experienced a slight increase in recent years, with an average of 129 cm in the 1992–1993 period. As a whole, there is a gradual fall from 1964 to 1971 and since about 1997.

The monthly water levels at the Saint-Louis station vary according to the totals discharged by the dam. They reach their maximum in October with, respectively, 1.32 m NGI<sup>1</sup>; 1.19 and 1.13 m NGI. There is nearly steady flow throughout the entire flooding period, becoming irregular after November. The minimum heights are recorded in May

<sup>1</sup> NGI measurements constitute the National Geographical Institute measurements of the various water levels.

**Table 1** Rules of management of the Diama Dam before the opening of the new mouth

Period	Objective	Level of reserve
Low water level	Increased level in the reservoir	+2.10 to +2.20 m NGI (since the low water level of 2001–2002)
Beginning of flood waves	Maintenance of an increased level for as long as possible, then lowering preventive when flood waves arrives reach Bakel	+2.10 to +2.20 m NGI then lowering to +1.50 m NGI
Period of flood waves	Level lowered in reservoir	+1.50 m NGI as long as flows are such that it is necessary to entirely open close the floodgates
End of flood waves	Raising the level of the reservoir as soon as possible	+1.50 m NGI then rising to +2.10 to +2.20 m NGI

with, respectively,  $-0.3$  m NGI;  $0.01$  and  $0.05$  m NGI. It appears that since 2004–2005, water level in the river has been decreasing constantly as a result of the opening of the new mouth. The hydrodynamic modifications generated by the opening have resulted in a disturbance of estuarine water circulation.

### Difficulties in the Management of the Diama Dam Following the Opening of the New Mouth

The opening of the new mouth has lowered water level at the Saint-Louis station. The opening of the new mouth has changed the flow conditions downstream of the dam to a share by lowering the average level downstream side making it more sensitive to the effect level of the tide (OMVS, Coyne and Bellier 2005). Thus, at the Diama Dam, the tidal range has significant changes. Before the opening of the new mouth estuarine, tides were semi-diurnal with heights rarely exceeding the meter during whitewater and  $0.5$  m during neap tides. Currently, the maximum daily tidal range recorded downstream of Diama Dam has tripled from  $0.30$  to  $0.93$  m near is noticeable throughout the year, including during the rainy season, which makes it difficult handling the valve system. This had an impact on the management of the Diama Dam. Since tides are the determining factors that influence the final stretch of the river, their variation determines water levels. Water levels downstream of the dam were substantial due to flood waves, whereas the upstream part experienced a sharp decrease in water level. This difference in height may cause the dam's failure. It has also become difficult to maintain water levels upstream for irrigation needs while ensuring the dam's safety. Following OMVS et al. (2005), management rules prior to the opening of the new mouth are shown in Table 1.

The new context has required various studies (IRD<sup>2</sup>-OMVS 2004; OMVS et al. 2005) financed by the OMVS in order to revise the rules of management at the Diama Dam. These studies have enabled a more flexible management of the dam to enable levels of  $1.50$  m to be reached upstream.

These installations on the Senegal River estuary have strongly disturbed natural hydrological function and strikingly pose the issue concerning the risk of serious flooding in the case of a rise in seawater level, hypersalinization of water in the lower estuary, the development of halophytic plants, the degradation of ecosystems, etc. In conclusion, these installations, which aim at alleviating extreme events of climatic origin, actually pose significant risks.

### Consequences of Water Management for the Senegal River Estuary

The changes introduced by the new mouth have clearly resulted in environmental impacts through disturbances in river water circulation. The new river mouth has resulted in a shorter residence time of freshwater since the part located downstream of the new mouth has evolved into a lagoon. The quality of water in the lower estuary remains close to that of the sea. According to Troussellier et al. (2004), salinity reached  $35$  ‰ more than  $12$  km south of the town of Saint-Louis. Since this section of the river has developed into a lagoon, exchange between marine and river water remains very limited. In fact, perturbations in the exchange between marine and river water and releases of salt from old deposits will certainly increase this salinization. The estuary is thus controlled by the Diama Dam and the marine dynamics by the opening of the new mouth. From the 2003 annual evaporation average ( $1,207$  mm), we have calculated the volume of water evaporated from the lagoon, which corresponds to more than  $13$  million  $m^3$ . This strong evaporation explains the excessive salinization of the lagoon, which will certainly impact the groundwater recharge of the lower estuary. The average salinity level measured in 2007 in the lower estuary was  $47$  g/l, which is higher the concentration than in seawater.

<sup>2</sup> Institut de Recherche pour le Développement: Research Institute for Development.

In addition, groundwater changes related to the developments of rivers are seen as a major issue in many parts the world. In Morocco, for example, following the construction of the Mohamed V Dam, the coastal wetlands of Moulouya are no longer subject to flooding from rivers, which is responsible for the recharge of groundwater used for irrigation. Both water and soil have become increasingly saline as arable lands are abandoned; this has caused farm workers to emigrate (Arthurton et al. 2008). Groundwater contaminated by saltwater intrusion makes inappropriate irrigated crops. The population around the lower estuary is highly dependent on groundwater which constitutes their irrigation system for market gardening. The problem remains severe since the opening of the new mouth; the salinization of groundwater has reached critical levels, causing an extension of the salt marshes and a progressive loss of farmland.

Important changes were noted in the coastal hydrodynamics such as the tidal patterns. During high tides, there is a large increase in marine water with an important evacuation of the river flows during low tides. The acceleration of coastal erosion cause real threats to the area. The mangrove swamp has shown a progressive degradation following the opening of the new mouth. The area of the mangrove swamp has fallen by 636 ha (or 59 %), from 1086 ha in 1979 to 450 ha in 2003 (Kane 2010). The area of the island of Doun Baba Dièye decreased by 8 % between 2003 and 2007, from 257 to 236 ha and now has completely damaged since October 2012.

Many villages such as Dieule Mbame, Tassinere and Keur Bernard (Fig. 2) are under threat. Resettlement of populations constitutes indeed a real problem as rehousing in the lower estuary is a big issue relatively to the availability of land.

#### Box 1: The opening of two new mouths

Recently, in October 2012, it has been reported that the two natural openings which are distant of 150 m have accelerated the process of dismantling of the sandy spit of “Langue de Barbarie,” and the disappearance of the coastal habitats. After having amalgamated with the breach opened in 2003, they reinforced the problem of the salinization of the grounds in the lower estuary.

## Risks Linked to Water Management in the Senegal River Estuary

The major risk in this area is linked to population settlements and the impacts of the various changes to the ecosystem and the resources. The Senegal River estuary

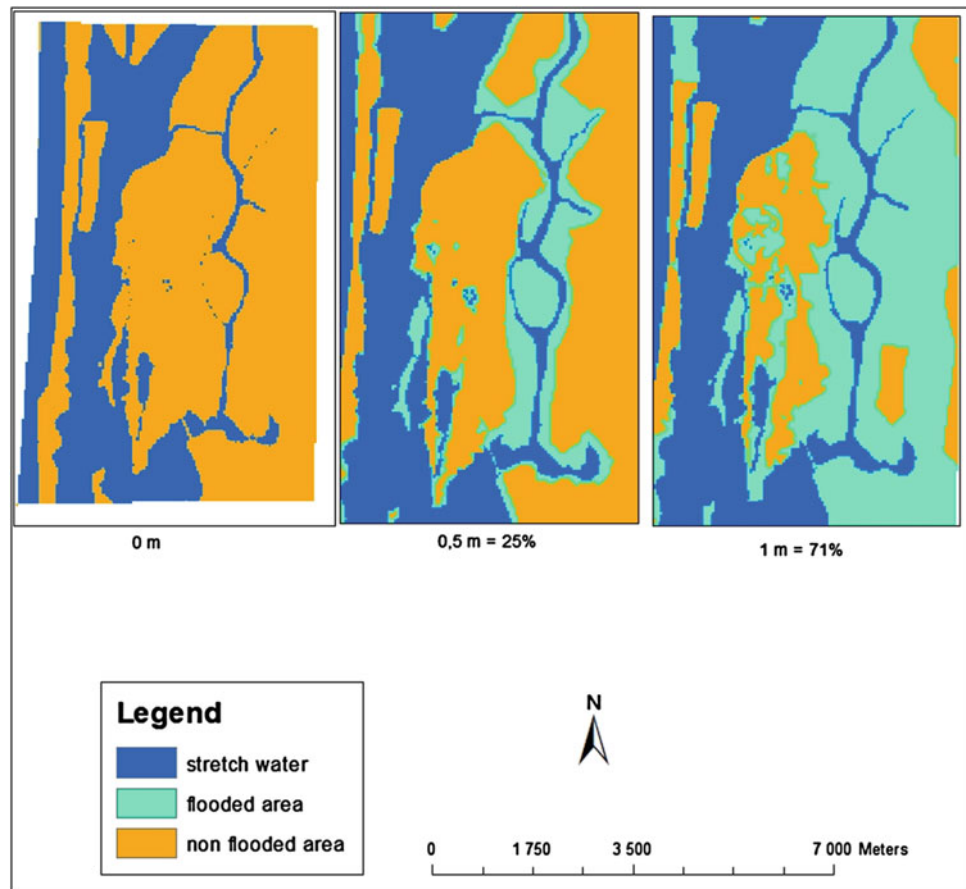
appears to be a risk-prone area, where the conjunction of several factors can produce incommensurable effects. Physical conditions (geomorphological, lower altitude) determine an area where risk is permanent and expose populations to hazard. Moreover, communities may aggravate the intensity or frequency of certain phenomena and the reach of their effects.

To prevent the occurrence of flooding requires the means to contain floods, such as the construction of dams or river dikes and the establishment of non-structural measures such as alarm systems for flood prevention, public participation, and institutional commitment (Tingsanchali 2012). However, the new opening of the mouth, which aims at reducing population vulnerability within the estuary, has been favored over precautionary principles. Also, questions concerning the human impact on risk aggravation are inevitably directed toward inquiring about negligence during establishment of these new developments, weaknesses in protection systems including alert and prevention, safety devices, and toward any negligence which may obstruct proper control and handling of these phenomena as well as reduction in the consequences.

Considering the impact of an extremely vulnerable area at the opening of “Langue de Barbarie,” which has had the consequences described above, the occurrence of a natural disaster will only increase the fragility of the system. It is probable that rising of sea levels will intensify environmental pressures and undermine sustainable development. This will result in higher risks of flooding and greater ingress of seawater while the lower estuary is already experiencing groundwater salinization due to exchanges between river and marine water following the opening of the new mouth. Populations located in low and coastal areas as well as in deltas and which are estimated to make up approximately 10 % of the world’s population will be particularly vulnerable to climate change (Nicholls et al. 2008; McGranahan et al. 2007). Simulations conducted by Durand et al. (2010), based on the potential height of water at the end of the rainy season and carried out for several scenarios for the rise in sea level, show that a 0.5-m sea-level rise would be enough to flood part of the town of Saint-Louis at times of annual high waters and that it would be almost completely submerged in the event of a 1-m rise.

Figure 5 represents the probable evolution of submergence of St-Louis based on increase in sea-level areas. It should be noted that the island and the sandy spit of “Langue de Barbarie” will be less affected than the “Faubourg de Sor.” The surface losses are 3 and 126 ha or 4 % of the territory up to 1 m. However, as we mentioned earlier, the “Langue de Barbarie” currently experienced recurring phenomena of coastal erosion. This situation can be explained by the importance of altitudes of more than

**Fig. 5** Flooded areas in the town of Saint-Louis in case of sea-level rise



6 m. It is mostly in the “Faubourg de Sor” that flood risk will be greater due to lower altitudes. The occurrence of extreme events is increasingly determined by the coincidence of hydro-climatic events affecting a changed environment by human activities (Bogardi 2004). This area is experiencing unplanned occupation which only exacerbates the risk of flooding in the case of sea-level rise. This shows that the ignorance of risk is a source of vulnerability. At a height of 1 m of submersion, 71 % of the city will be under water. The entire area east of the city will be particularly affected.

The realization of large-scale new developments in sensitive areas may show a lack of perception by communities of the risks involved. Lefèvre and Schneider (2002) stress that extreme difficulty in risk recognition and management is due to their limited perception by human communities. The exposed population’s lack of perception of their own vulnerability to natural disasters is itself a factor of vulnerability which will constrain the establishment of preventive measures (Leone and Vinet 2006). Thus, the estuary of the Senegal River appears vulnerable and subject to the shock of unforeseeable and uncontrollable devastating events.

## Conclusion

Management of tropical rivers can increase risks and vulnerability. In the Senegal River, it has resulted in consequences that impacted seriously the functioning of the estuary. The sea-level rise and the rapid erosion of beaches are not always mastered. In spite of the estuary’s particular nature, it has been subject to developments carried out without preliminary studies in regard to their impact. The resulting changes may be determining factors in the evolution of the local environment. In the Sahel, despite the large climatic variability which causes events of extreme nature, risk-related consequences have not been sufficiently considered. Preventive measures seem not to be related to knowledge of risk, but to knowledge of this perception.

The new mouth has created a dysfunctioning which, in the long term, will have much more significant repercussions. The consequences of these modifications generally erode resilience of the system, which has difficulty resisting, to adapt to a major change. The rise of sea level in the lower estuary would flood most low ground, causing damage to the socio-ecological system. Such a rise would constitute a



serious threat to the socio-ecological system in addition to having serious consequences geomorphological and socio-economic. Nevertheless, knowledge and perception of risk play a fundamental role in the policies of prevention concerning risks. Even if the latter appear to have been controlled, there has not been sufficient consideration of the consequences associated with the prevalence of risk, which can generally lead to irreversible actions. Considerations of risk in the various management policies are of significant interest in a context characterized by an increase in disasters.

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