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Multi-scale analysis of island formation and development in the Middle Loire River, France

EMMANUÈLE GAUTIER & STÉPHANE GRIVEL

University Paris 8, Dept of Geography and CNRS Laboratoire de Geographie Physique, 1 Place A. Briand, F-92195 Meudon Cedex, France

emmanuele.gautier@cnrs-bellevue.fr

Abstract Vegetated islands in the river represent very specific fluvial landforms dominating the landscape of the middle Loire River. Our aim is a better understanding of island formation, planform evolution channel adjustment over different spatial and time scales. A number of approaches were adopted. First, the analysis of historical maps and aerial photographs reveals the recent development of islands, allowing the determination of different types of islands associated with specific evolution mechanisms and mobility rates. The second approach is based on the comparison of cross-section profiles of the river bed at multi-decadal time scales. This part of the study used precise topographic surveys and sediment trapping systems coupled with grain-size analyses to evaluate the annual deposition and erosion. The impact of two floods of different magnitudes, with return periods of 5 and 30 years, was also investigated.

Key words environmental change; floods; fluvial islands; France; Loire River; sedimentation rates

INTRODUCTION

With a basin of 112 120 km^2 and a length of 1012 km, the Loire River is one of the major fluvial hydrosystems in France, and it is well known as one of the "last wild rivers of Europe". Its hydro-dynamics have remained relatively natural, creating a great diversity of fluvial landforms including mobile meanders and multi-thread channels, although locally engineering works have modified this diversity. In the middle reaches of the river the fluvial landscape is dominated by islands occupied by a patchwork of alluvial forest, shrub and prairie (grassland).

This study is a contribution to the knowledge of the fluvial islands; few studies have been conducted on these specific fluvial landforms. According to Osterkamp (1998, p.530) "a fluvial island is defined as a geomorphic feature, surrounded by channel, that is higher than mean water level … and that persists sufficiently long to permit the establishment of a permanent vegetation cover if adequate moisture is available". Fluvial islands are commonly observed on anabranching fluvial systems and in fluvio-deltaïc environments (Knighton & Nanson, 1993; Nanson & Knighton, 1996). Accepting the statement that "fluvial islands provide excellent information on recent geomorphic history and process" (Osterkamp, 1998, p.530), the aim of the present work is to understand further the dynamics of fluvial islands of the River Loire in terms of the processes of formation, evolution and behaviour.

The analysis of the fluvial islands was carried out at different temporal and spatial scales. The first step consisted of a historical assessment of island development over

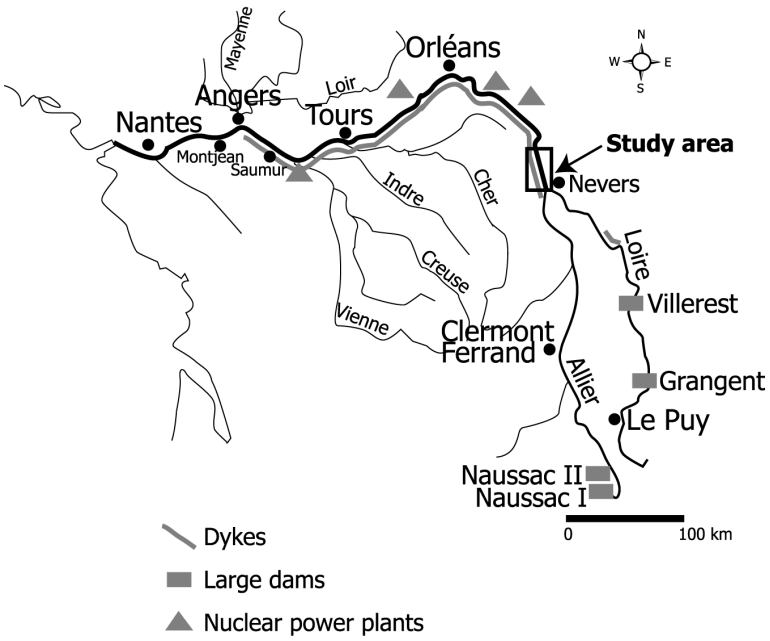

Fig. 1 Location map.

the period 1850–2002. This evaluation concerns approximately 100 islands located downstream of the Allier River junction, the main tributary of the Loire River (Fig. 1), and seeks to determine the evolutionary schemes of these islands, including specific sedimentary processes and mobility rates. The second part of the study analyses the deposition and erosion rhythms at two time scales: since the 1970s, and at an annual time scale since 2002.

HISTORICAL APPROACH TO FLUVIAL ISLANDS DYNAMICS

Sources and methods

The temporal evolution of fluvial landforms on the River Loire was analysed using: (a) two sets of precise topographic maps: 1850 and 1933; and (b) three sets of aerial photographs: 1960, 1995 and 2002. Multiple morphological features were measured, considering both synchronic and diachronic processes, including the active channel (composed by the channels and the unvegetated bars), delineation of vegetated forms (islands and lateral margins), calculation of areas for each type of fluvial unit and characterization of the vegetation. All data were integrated in a GIS (ArcGis). Earlier maps, from the 18th century, were also used to analyse planform development over longer time scales, but it was not possible to integrate them into the GIS because of their geometric distortions.

The recent development of fluvial islands

Although several islands can be observed on ancient maps (middle of the 18th and 19th centuries), their development is recent. In 1850, only 11 islands occupied 4% of

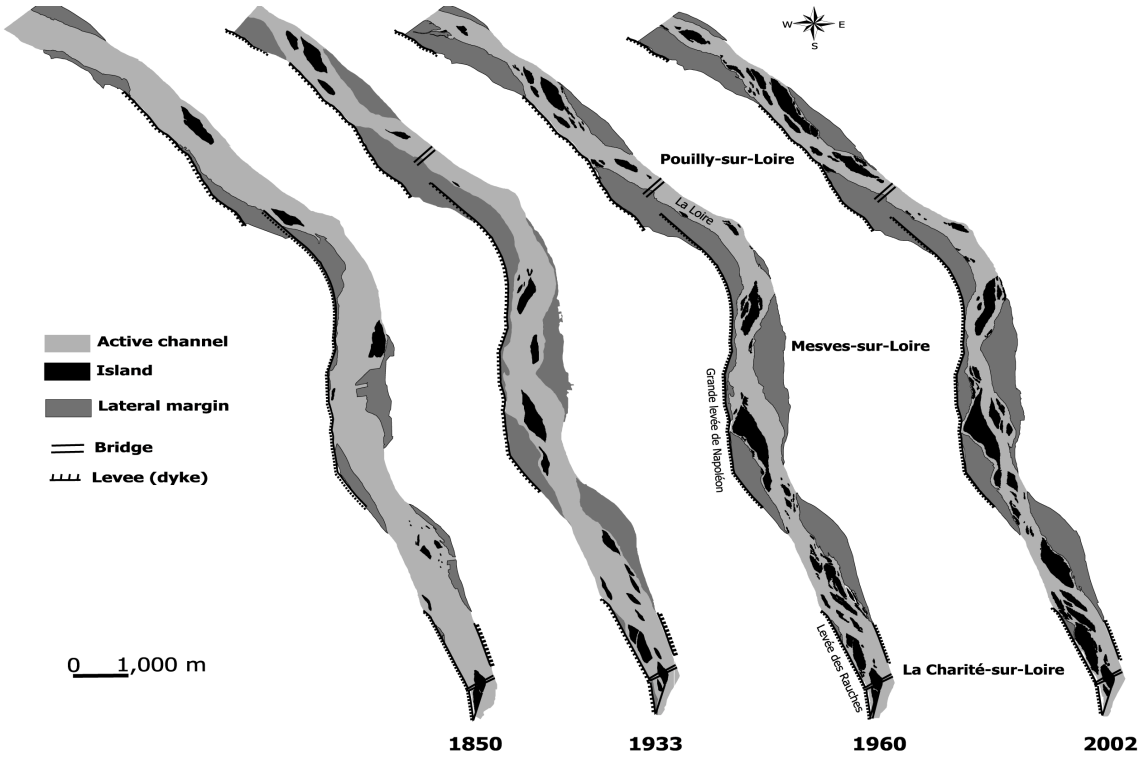

Fig. 2 Historical change of the Loire River's fluvial bed (La Charité-sur-Loire/ Pouilly-sur-Loire section).

the valley floor (Fig. 2). At this time, the Loire featured a wide and active channel, largely free of vegetation, that occupied more than 75% of the fluvial bed that is limited by the dyke on the left hand side. One hundred and fifty years later, the fluvial landscape has drastically changed showing an important reduction of the active forms and a huge expansion of islands and lateral margins. The vegetated landforms presently occupy 60% of the fluvial bed (18% for the islands and 42% for the lateral margins). This change of the fluvial forms is accompanied by a marked transformation of the vegetation mosaic (Gautier *et al.*, 2000, 2001); the percentage of naturally forested land (hygrophilous and mesophilous woodlands) having increased from 0.43% to 35% in the fluvial bed since 1850. Softwood alluvial forests (*Salix alba*, *Populus nigra* and *Acer negundo*) and hardwood forests (*Quercus robur*, *Ulmus minor*, *Ulmus laevis*, *Fraxinus excelsior*) colonized 90% of the islands' area. During the same period, pioneer sequences (essentially composed of young *Salix trianda*, *Salix purpurea*, *Salix trianda* and *Populus nigra*) typically associated with channels and bars that are exposed and dewatered during summer, and prairie communities at higher and drier levels, experienced a significant decline (15% of the valley bottom in 1850; 1% today).

Behind this general evolution of the valley floor, that could be considered as a "fluvial metamorphosis" (Schumm, 1969), a more complex evolution can be analysed concerning the islands. First, the calculation of an annual accretion rate (annual area increase/total bed area) enabled the determination of island dynamics. The annual rate reveals an acceleration of the formation of islands: it has been more than three times higher post-1933 (+0.15%) than during the previous period (+0.04%). This accretion

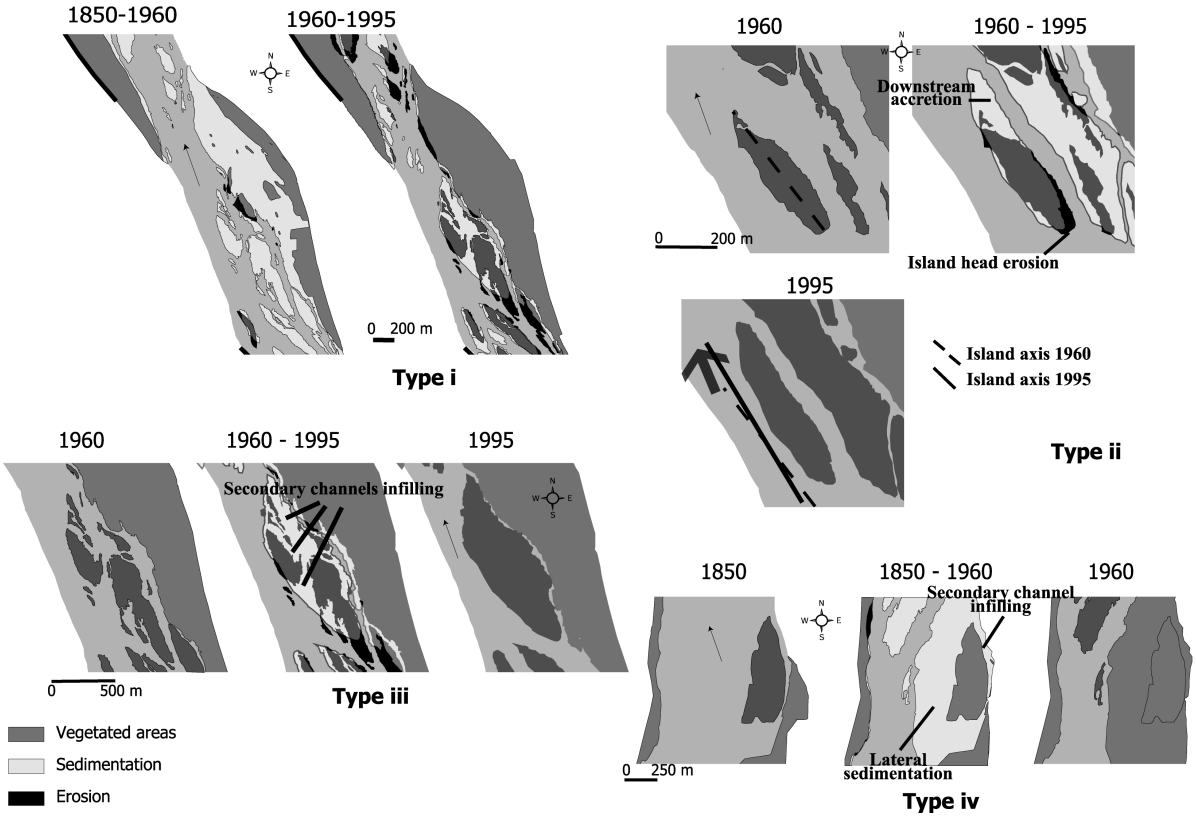

Fig. 3 Evolutionary models of the islands of the middle Loire River

rate remains relatively stable post-1933, varying between +0.15 and +0.17%. Second, the precise study of the shape, size, position and axis of the islands at different dates underlines the complexity of their evolution. Among the numerous islands studied, four main types can be distinguished with regards to their evolution pattern and the following classification is based on a relative mobility gradient (Fig. 3).

(i) The first type is composed by ephemeral islands characterized by a rapid formation of a single narrow and elongate island followed by rapid erosion. This case concerns only small islands: their size never exceeds 4000 m^2. This observation does not imply that all small islands have been subjected to erosion.

(ii) The second type groups together mobile migrating islands. These large and elongate islands are subjected to erosion of their head and a progressive accretion in their downstream part. The mean migration is 3 m $year^{-1}$. Because downstream accretion exceeds head retreat, the size increases progressively. This migration concerns important islands, whose size exceeds 100 000 m^2.

(iii) In the third group are very large and stable island systems. Their origins are linked to the presence of clusters of small islands, which as a result of rapid infilling of the secondary channels that formerly separated them, eventually coalesce.

(iv) Finally, the fourth group is composed of stabilized islands that have been connected to the lateral margins.

Thus fluvial island evolution is geomorphically complex and it must be recognized that stability is a relative term depending on the time scales under consideration.

EVOLUTION OF ISLANDS: A FINE SCALE ANALYSIS

Methods

Several flood plain cross-sections measurement were undertaken in 1970 and 1995 by the Loire Basin Water Survey; they were repeated by us, every year since 2002, using a RTK GPS coupled with a total station. Three interesting examples of cross-sections are presented in Fig. 4; they cross the flood plain from the artificial levee on the left bank to the right side of the flood plain. These cross-sections are employed to determine the activity rate (i.e. erosion and sedimentation rate) for each fluvial unit, including islands, for a period of 25 years (1970–1995) and at an annual scale since 2002.

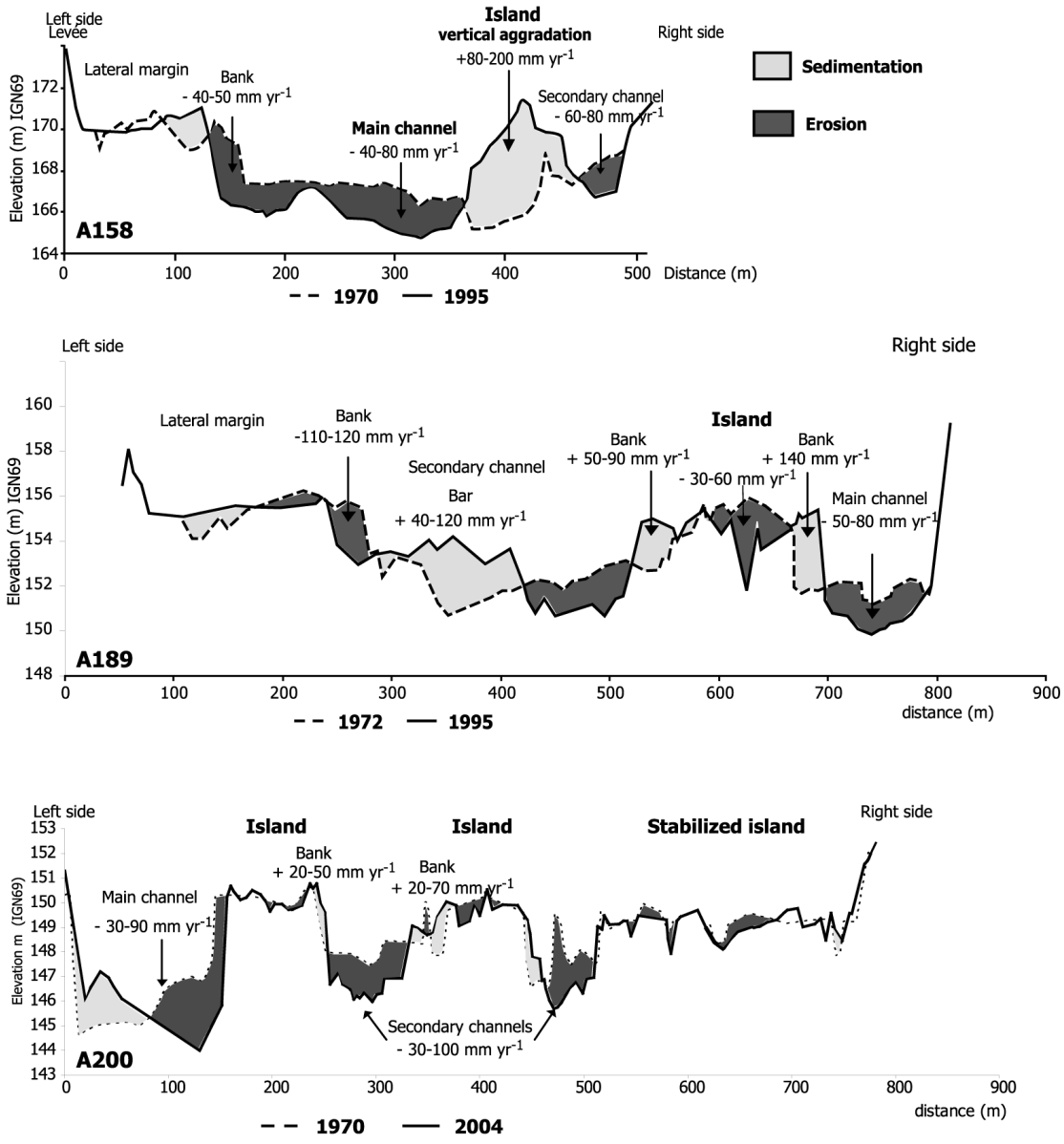

Fig. 4 Multi-decadal evolution of the flood plain topography of the middle Loire River: three examples of cross-sections.

To provide information on the spatial distribution of sediments within the functional units, samples were collected along the cross-sections. After collection, grain-size distributions were determined: coarse sediment (>1.6 mm) was analysed with standard sieving and the finer fraction by laser granulometry. Although there are a number of parameters that can be used to characterize the particle size distribution, in the present study the median (D_{50}) and the coarser percentile (D_{99}) of each sample were used, as these two textural parameters are the most significant regarding the transport and depositional processes of particles (Passega, 1957).

To determine the annual deposition on islands, sediment trapping systems were installed along several cross-sections; this paper presents the results of the three islands located in the A200 cross-section (Fig. 5). Grain-size analyses were also conducted on the collected sediment.

Accretion and erosion mechanisms of islands

Two contrasting accretion rates and mechanisms were recognized from the survey data. The first type is represented by small narrow islands which were entirely deposited between 1970 and 1995. These youngest islands (see cross-section A158 in Fig. 4) show a rapid vertical accretion varying between 80 and 200 mm $year^{-1}$ and 5 m of sediment have been deposited within the Bec d'Allier island since 1970. Stratigraphic sections reveal a fining-upwards sequence (vertical grain-size decrease) with the upper 0.4 m associated with a graded suspension (medium and fine sand), whereas the lowest sections reveal coarse sand and gravel. The islands represented on cross-sections A189 and A200 constitute the second type, which is more complex due to the longevity of the form. In this case, the island development is mainly associated with lateral aggradation on the islands banks. The deposition rate varies between 50–140 mm $year^{-1}$. All these lateral deposits present specific textural features. The crests of the most active and highest banks are made of medium and/or fine sand transported by graded suspension overlying gravel and sand transported by rolling. The central part of the oldest islands is less active with fine deposits of silt and fine sand.

Comparative analysis of two recent but unequal floods

During the study period, two floods of differing magnitude submerged the islands: February 2003 with a discharge of 2200 m^3 s^{-1} (frequency of 5 years) and December 2003 with 3450 m^3 s^{-1} (frequency of 30 years). Topographic surveys obtained before and after each flood indicated that the first produced a uniform deposit of fine sand and silt that rarely exceeded a depth of 50 mm (Fig. 5). By contrast, the high flood of December deposited sediment wedges 0.2 and 0.5 m thick on the left and right banks, respectively, of the youngest island, whilst on other islands the flood unit was typically 0.15 m thick. These data emphasize the importance of large floods on the accretion rate and the significance of lateral accretion as a process of island expansion. Topographic surveys were also completed on secondary channels, demonstrating infill ranging between 0.2 and 0.8 m after the flood of December 2003.

Complex response of the system to hydro-climatic and socio-economic changes

The islands express a complex response of the fluvial system to various factors that act at different time scales. Chronologically, the initial factor affecting the channel system was the fact that the Loire River has undergone a strong decrease in large floods since the end of the 19th century (Dacharry, 1996). At the end of the 18th century and during the following decades, four extreme events (with a supposed return period of 150

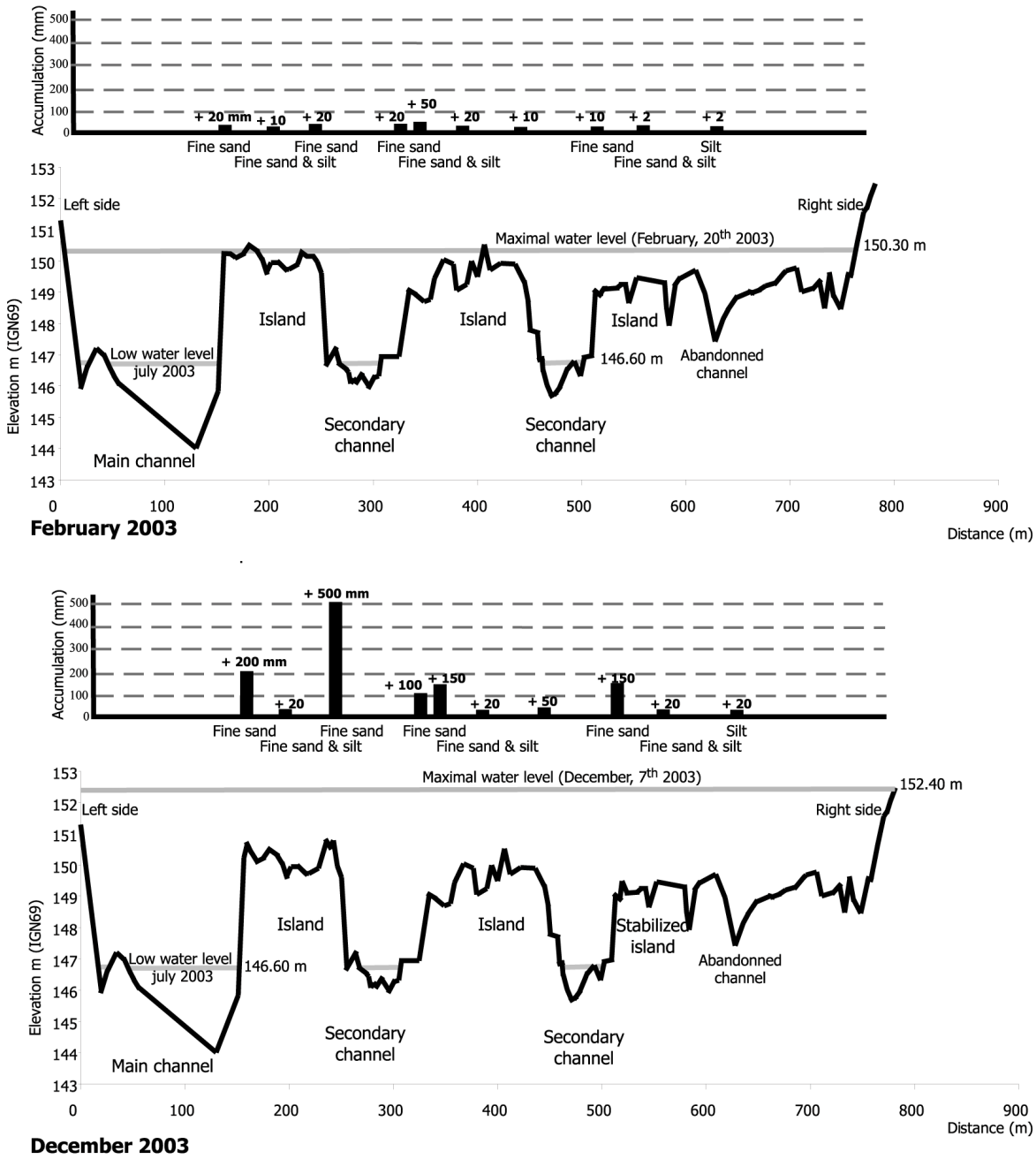

Fig. 5 Deposition on islands during two floods (A200 cross-section).

years) were registered in 1790, 1846, 1856 and 1866, with the latter event peaking in discharge at 7000–7500 m^3 s^{-1} in the middle Loire River. All the hydrological events since 1866 were characterized by floods of lesser magnitude, with only six peak discharges between 3000–4150 m^3 s^{-1}. Therefore, the flood of December 2003 constitutes one of the highest discharges of the last decades.

Investigations were also undertaken to characterize the processes and scale of social and economic change within the Loire basin that could have affected the development of the channel system (Gautier *et al.*, 2001). First, the long-standing use of the Loire River as a navigation channel suffered heavily from competition with railways and road transportation, and decreased tremendously at the beginning of the 20th century. This had a major impact on the riparian vegetation because to maintain the navigation channel aquatic macrophytes and riparian communities were regularly cut. With the decline in the use of the river for navigation many of the maintenance works were abandoned and programmes such as those removing woody debris from the channel were abandoned. The rapid decrease of navigation is probably one of the main causes of the island rate acceleration observed during the first decades of the 20th century.

Recent studies have also recognized the decline in traditional land uses, that clearly enhanced the colonization of important parts of the flood plain by riparian vegetation. Important areas on lateral margins and islands were cultivated or pastured until the late 1960s. Finally, several studies suggest that incision of the main channel was a response to massive gravel extraction in the active bed (Gautier *et al.*, 2000, 2001; Gazowski, 1994). A maximal entrenchment of 3 m at the Allier River junction occurred (Fig. 4), the incision decreasing downstream (1–2 m). The incision has left bars suspended above the main channel, and thus reducing their submersion duration and favouring their colonization by vegetation.

CONCLUSION

In the case of the Loire River, fluvial island development is indicative of ongoing adjustment of the fluvial system to physical factors (reduced water and sediment discharges) and socio-economic pressures that act almost synchronously with regards to the long-term hydromorphological evolution of the system. This study integrated the historical scale together with the event (flood) scale, and confirms the strong interactions between fluvial dynamics and biological factors. Vegetation growth clearly responds to the reduced capacity of the fluvial bed and to changes of human use, but it also exerts a major effect on sediment trapping.

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