Alpine alluvial landscapes and biodiversity

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Riparian vegetation communities along watercourse provide specific habitats at the land-water boundary, where water, sediment and energy flows interact with the vegetation itself. River dynamics is at the origin of ecological and hydromorphological processes responsible for the high spatial and temporal variability of environmental factors. Biodiversity varies longitudinally from source to mouth and transversely from open water areas to backwaters periodically flooded by floods. It is also closely dependent on underground flows. As rivers are highly responsive to climate change and human activities affecting watersheds, most rivers have been artificially regulated over the past two centuries. The result has been a significant erosion of biodiversity, the restoration and management of which nowadays requires the search for a sustainable river dynamic and guaranteeing the regular renewal of riverine habitats.

1. Plants adapted to floods

Alluvial plant communities are **transitional** areas between **aquatic and terrestrial environments** that are constantly being remodelled by river activity [1]. Under the pressure of imposed constraints, plants have developed **adaptive responses** that allow them to settle, develop and reproduce in these habitats subject to the influence of water, energy and material flows [2]. Adaptive responses are expressed as:

highly developed root systems that effectively fix deposits and resist erosion and current;

an **ability to recover** from the stems and branches buried in the sediments;

an ability to rapidly **colonize** favourable environments by vegetative reproduction (rhizomes{end-text} A more or less elongated perennial underground stem, branched or not, provided with leaves reduced to the state of very small scales, emitting adventitious roots each year and an apical bud that gives rise to an aerial stem, slightly buried in the ground in which it grows horizontally or flush with the surface.{end-tooltip}) and by dispersing many seeds by water and wind.

physiological adaptations to withstand prolonged periods of anoxia.

Plants thus resist the stress imposed by floods, whose frequency, intensity, extent and timing of the biological year in which they occur are highly variable. The ability of the river to create new environments through **river dynamics** explains the high **biodiversity** because various habitats are then made available. The plants found there, such as willows and poplars for example, are closely dependent on disturbance for their spread and reproduction. Plant development after germination is linked to the presence of exuberant deposits{ind-text} to be exempted: to emerge after a flood{end-tooltip} and to be stable over periods ranging from the biological year for annual pioneer species to the century for perennial species in mature hardwood alluvial forest.

2. Spatial and temporal organization of the riparian landscape

Figure 1. The role of pioneer vegetation in the construction of sandy banks. On the left, a young pioneer plant (Agrostis stolonifera) settles between the pebbles, resists the force of the current thanks to its strong rooting and traps sediment. On the right: the deposition increases in volume, the tussock expands and other species such as Calamagrostis pseudophragmites settle. [Source: Photos © J. Girel]

In the **alluvial plain** water flows, fluxes and size of transported sediments and vegetation are the main environmental factors. Vegetation will fix the banks, trap the sediments (Figure 1) and then create large debris jams will influence the distribution of flows. The interaction between physical and biotic processes creates a permanent change in the distribution of terrestrial and hyporheic habitats [1]. High biodiversity is observed in these ecosystems where competitive species that monopolize stabilized habitats coexist with fugitive species adapted to stress that characterize intermediate levels of disturbance [3]. These **plant communities** are **spatially organized** in three dimensions.

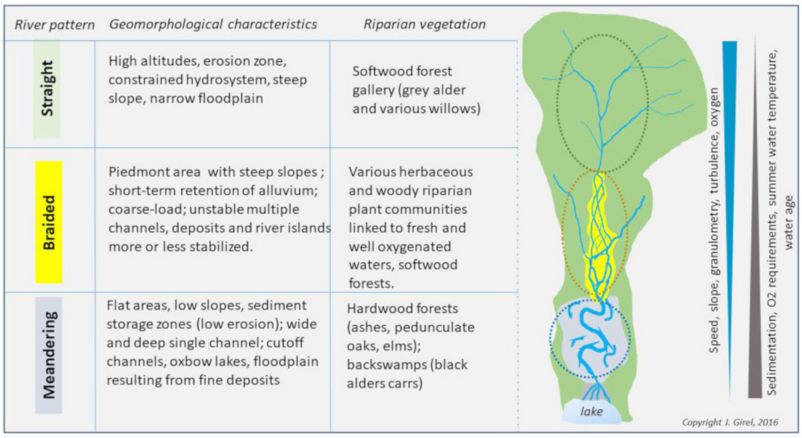


Figure 2. Geomorphological areas, river models and biodiversity. [Source: Schéma © J. Girel]

Longitudinally. The supply of water, materials and nutrients transported increases from the source to the mouth of the river; however, the slope and flow velocity decrease. As a result, geomorphological models are modified (Figure 2) and it is in the middle sections that the highest biodiversity is found [4]. For example, the shrubby and herbaceous plant layers growing under white alder groves are the richest in species below 800 metres in the braided piedmont area [5].

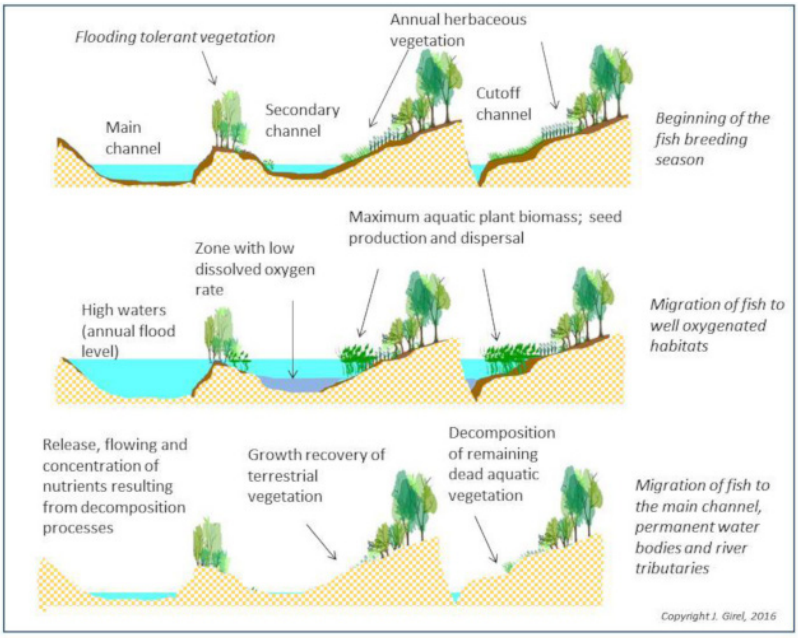


Figure 3. The river lateral annexes are connected or separated from the active main channel according to seasonal variations in water level. [Source: Scheme © J. Girel]

Laterally. Seasonal variation in water levels leads to lateral channel dynamics and controls alluvial species recruitment and nutrient redistribution [6] (Figure 3). The impoundment times of the river annexes vary according to the distance to the functional channels.

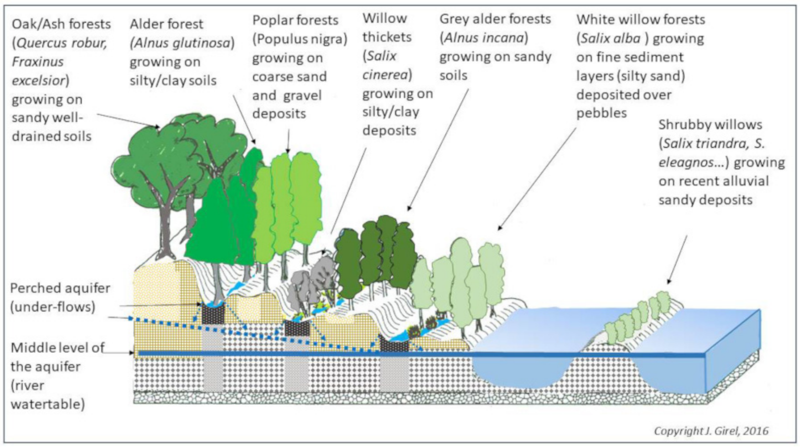


Figure 4. Topographic and water locations and vertical connectivities provide ecological optimizations for various terrestrial and hyporheic zones species and communities. [Source: Scheme © J. Girel]

Vertically. Various species and communities living in the hyporheic or terrestrial zones depend on the underflows and depth level of temporary groundwater as well as variations in the permanent groundwater table (Figure 4).

In addition, the riparian landscape is still in a state of transition between an old state that can be reconstructed and a future state that is difficult to predict.

3. Ecological and hydromorphological processes

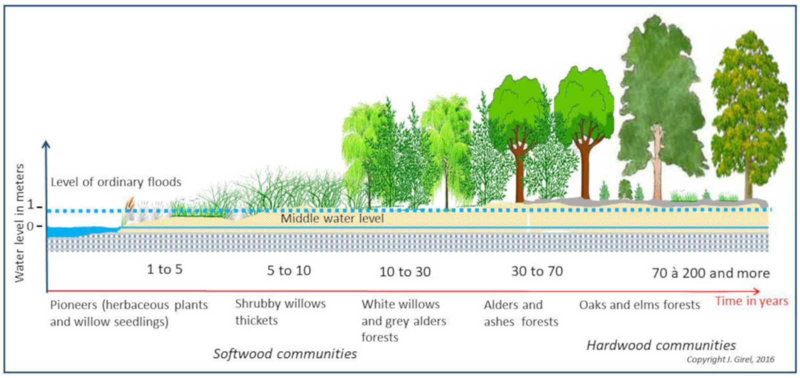


Figure 5. Chronosequences of plant succession on an alluvial deposit. [Source: Scheme © J. Girel]

The plant-succession. On stabilized deposits, vegetation changes over time. The plant species established give way to new arrivals species which compete for resources. The composition of plant communities – and therefore biodiversity – changes from herbaceous, then shrubby and softwood tree stages to hardwood forest stages (Figure 5). This evolution is explained by changes in internal ecological conditions that are controlled by the plant community (autogenic succession) or created by external factors. In this last model, called allogenic succession, -the most common along dynamic watercourses- floods deposit alluvium that favours the establishment of new species. In this case, an allogeneic succession by facilitation is initiated; it results in an increase in biodiversity during the transitional stages. The terminal stage of mature hardwood forest then evolves through slow autogenic processes that act at the soil level with the participation of fungi and bacteria (Figure 5).

The zonation. The deposits produced by a dynamic watercourse are composed of clay, silt, sand, gravel and pebbles in varying proportions. They have thicknesses and structures that explain the presence of a mosaic of habitats also characterized by surface and subsurface hydrology (see also Figure 4). Species replace and organize themselves according to local environmental conditions. As with succession, the areas are highlighted by one or more dominant species (Figure 6).

Figure 6. Zonation on a side bar of the Isère downstream of Albertville. [Source: Photo and scheme © J. Girel]

Flow, transported load, river pattern and vegetation. When flows are sufficient and the bedload is abundant and mobile, the slope increases to ensure downstream transport. However, the stream does not have a flow rate capable of discharging all its bedload by the way of saltation process; consequently, its alluvial floor rises. The resulting multiple river channels and islands form a braided system (Figures 2, 7a and 8). The constitution and lifespan of islands and channels vary according to the intensity and frequency of flooding, which allows for the existence of various habitats on porous deposits. The latter particularly shelter ligneous species that characterize the fast and oxygenated waters such as grey alder, black poplar, sea buckthorn, German tamarisk and various shrub willows.

Figure 7. Tagliamento, Italy, braided stream (a, left); La Morava, Czech Republic, meandering stream (b, right). [Source: photographs J. Girel and X]

When the river discharges are high and bedload material in small quantities, the transport capacity of the watercourse exceeds the energy consumed. This results in a deepening of the bed, an elongation of the river course, a lowering of the slope and the formation of meanders. Floods deposit fine materials from the suspended load. This river pattern is characterized by habitats that support species such as black alder, alder buckthorn or grey willow, adapted to slow, low-oxygenated waters and compact soils (Figures 2 and 7b).

4. Human influence over the long term

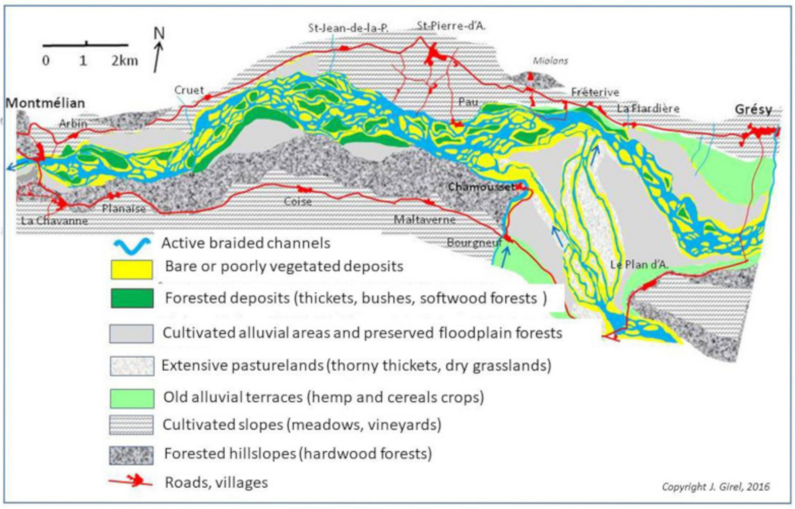


Figure 8. Land use and biodiversity in a braided alluvial floodplain, the Isère valley in Savoie (downstream of the confluence of the Arc) at the end of the 18th century. [Source: Scheme © J. Girel]

River metamorphoses and biodiversity. Alpine rivers drain watersheds subject to climatic hazards and changes in use. Very reactive, they have undergone several river patterns metamorphosis in the past [7]. For example, during the Little Ice Age{ind-text}A period marked by significant winter cooling and short summers in Europe and North America. It lasted for more than 400 years, from the early 15th century to the mid-19th century.{end-tooltip}, the excess load, due to increased precipitation and erosion on bare slopes, was at the origin of the development of braiding in the piedmont area. The braided river landscape, with vegetated islands and multiple channels, is one model among others in the Alps (Figure 8) nevertheless it contains probably the highest biodiversity. This assumption, confirmed on "natural" braided rivers [8], is consistent with the hypothesis of intermediate disturbance [3].

19th century: modifications to the structure of the alluvial landscape. In the 19th century, braided rivers were diked and fluxes (water, sediment and energy) were controlled by diversion, warping and drainage works that altered the floodplain area located outside the diked channel [9].

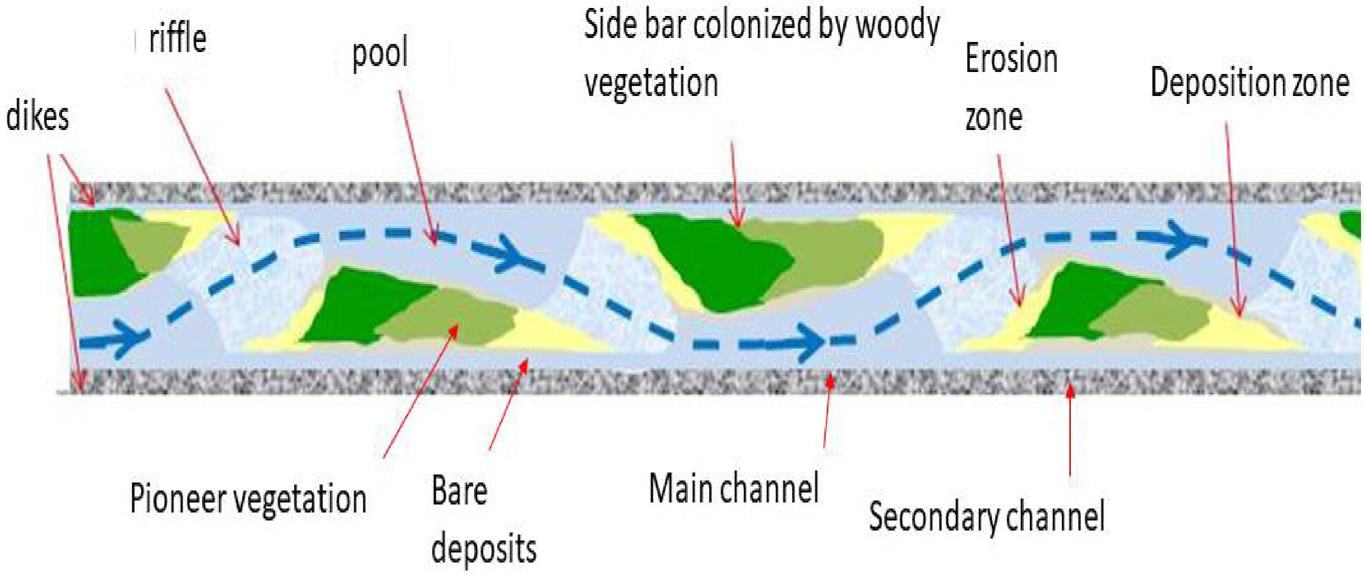
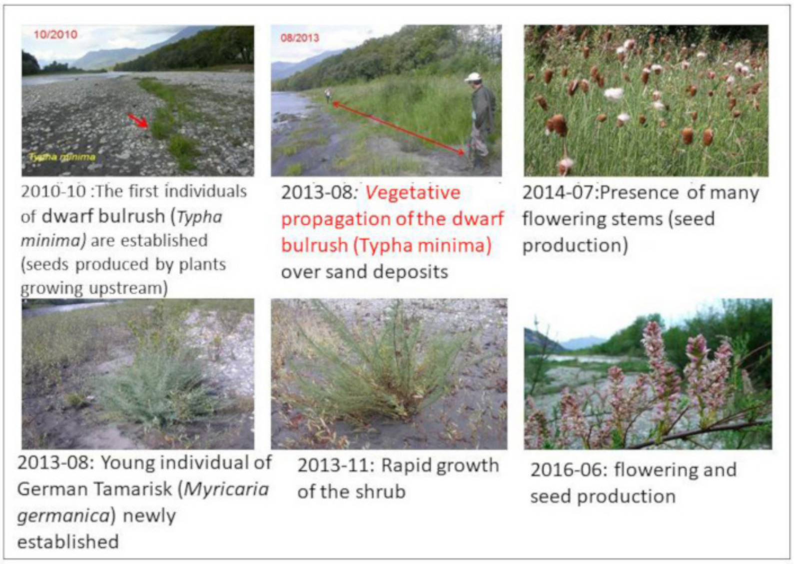


Figure 9. Formation of side bars in a diked channel. [Source: Scheme © J. Girel]

The simplification of the system [10] affects biodiversity at the landscape level [11]. On the other hand, outside the dikes, alkaline fens are expanding. In the rising artificial bed, the succession of riffles and pools leads to the formation of side-bars (Figure 9). These mobile lateral deposits, specific to diked rivers with steep slopes, are the last refuges for plants growing usually within braided systems.

20th century: erosion of biodiversity. In watersheds, declining precipitation and the vegetalization of bare land have had an impact on river dynamics since the beginning of the 20th century. Reduced runoff on stabilized slopes limits erosion; in addition, much of the sediment is stored upstream in hydroelectric reservoirs. The result is a coarse load deficit that results in bed deepening, accentuated by gravel extraction from rivers. There is then a stabilization of lateral deposits. The annual floods, mitigated by dams, are no longer sufficient to mobilize the bedload that can renew hydromorphological landforms. On the other hand, ten-years floods occurring during the vegetative period create spectacular aggradation increasing the stability of river islands and side bars. This results in a loss of biodiversity by homogenization of vegetation remaining at the woody stages characteristic of the end of the plant-succession. Early succession plants such as the dwarf bulrush, linked to dynamic watercourses, are threatened with extinction. The same applies to willows (six species present), german tamarisk, sea buckthorn, black poplar and grey alder, a tree typical of the Alpine foothills. Heterogeneously structured alluvial communities, composed of native species with natural self-regeneration, are giving way to homogeneous, stable and highly exotic species-impregnated communities.

21st century: revitalizing watercourses. Afforestation of river islands and side bars reduces the capacity of the diked channel, which is no longer able to provide transit during exceptional floods. The protection of highly anthropized alluvial floodplains requires appropriate development. Where possible, the river's freedom space can be extended or retention basins can be created outside the dikes in areas reserved for alluvial forest, poplar plantations or wet grasslands and marshes. However, deforestation and levelling of river islands remains a necessary step to ensure the safety of people and property and the conservation of biodiversity. Within the channel, biological richness effectively depends on the creation of bare spaces where the initial phases of plant succession will begin. Large trees that can generate big debris jams are prohibited.



2010-10 :The first individuals of dwarf bulrush (*Typha minima)* are established (seeds produced by plants growing upstream)

2013-08*:* Vegetative propagation of the dwarf bulrush (Typha minima) over sand deposits

2014-07:Presence of many flowering stems (seed production)

2013-08: Young individual of German Tamarisk (*Myricaria germanica*) newly established

2013-11: Rapid growth of the shrub

2016-06: flowering and seed production

Figure 10. Colonisation of a side bar in the Isère river valley of Savoie by Typha minima (dwarf bulrush), a protected species, emblematic of alpine rivers, and by Myricaria germanica (German tamarisk), a threatened species. [Source: Photos and scheme © J. Girel]

21st century: managing flows to conserve biodiversity.Water and material flows must be reserved to ensure the creation of habitats favourable to the dispersal, germination, survival and reproduction of alluvial species. For example, the ten-year flood of May 2010 was positive for the recolonization of the side-bars of the Isère that had been levelled the previous winter. In July, black poplar, several species of willows (*such as Salix daphnoides*), German tamarisk and various herbaceous plants were established, including the dwarf bulrush. This rare species then spread as the German tamarisk bushes thrived (Figure 10). As self-regulation of the restored hydrosystem is recommended, to encourage regular renewal of the alluvial landforms, the manager will be able to use two levers: solid flows (coarse bedload) and liquid flows. Flow manipulations must be tested in synergy with the managers of hydroelectric plants. At the same time, modelling work is also required to determine which parameters of artificial disturbance to create, in terms of amplitude (instream reserved flows [12]), extent and timing with similar adaptive responses [13].

5. Reference state for biodiversity restoration

Climate, alpine colonization and development of braiding. In the case of alpine rivers, there has been shown a significant increase in the volume of coarse materials transported during the *Iron Age* (2700/2400 BP), the *post-Roman period* (500-700 AD) and the *Little Ice Age* (1550-1850). With the increase in rainfall, human activities, such as deforestation and the development of agriculture on the slopes, were the main causes. These changes were then at the origin of the braiding process proved by the paleochannels recorded in the sediment levels dated from these periods [14].

Old maps and representation of a reference state. During the *Little Ice Age*, the piedmont rivers presented the full range of habitats (about forty plant communities) associated with the so-called “braided system with vegetated islands”. This diversity represented by the 18th and 19th century maps (see Figure 8 and [9]) suggests that the braided system offers all the features of the reference mode [15] for the renaturation of the Alpine floodplains. Returning to a natural state is highly debatable here because many communities with high biodiversity are the result of human exploitation of plants [16]. Moreover, for socio-economic reasons, restoring the landscape prior to diking works is utopian.

Figure 11. The Arc, on several sites (here upstream of Aiguebelle, Savoie), has a bedload allowing braiding in an enlarged river-freedom space ; the silty sand deposit in the foreground is a suitable habitat for the dwarf bulrush. [Source: Photo © J. Girel]

However, by restoring more space of freedom to the river, we significantly increase biological richness. This application of the “String-of-Beads Restauration Concept” [17] confirms that it is not necessary to redevelop the entire river corridor to restore most of its ecological potential. Through a river dynamic restored in a few sections, we obtain a regular renewal of habitats. These sites are reservoirs of biodiversity. Present on rivers such as the Arc (Figure 11), they ensure the establishment of large communities of dwarf bulrush [18], sea buckthorn and German tamarisk on the river islands of the Isère downstream. Many species, usually found at high altitudes screes (so-called dealpine species) are also frequent.

Future of alpine alluvial biodiversity. One of the major issues related to global warming will be water management and its impacts on river ecology. If the policy of renaturation of the alluvial plains by increasing the reserved flows [12] was not pursued, it would be necessary to expect a significant change in the spatial organization and biodiversity of riparian landscapes.

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Cover image. Vegetation of a braided stream: Tagliamento, Italy. [Source: © Photo J. Girel]

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