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Safety management or the promotion of biodiversity

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Introduction: riverbanks in the French Prealps often reinforced with protection structures, can play a major ecological role.

Embankment

- 1 Since the Middle Ages, rivers in the French prealps have often overflowed, causing flooding and silting of cultivated lands or their transformation into marshes, and sometimes even the destruction of residential areas. Embankment work began in the late 17th Century, and was developed and intensified well into the 20th Century (Bravard, 1989).
- 2 In the French Alps, out of more than a thousand kilometres of braided rivers, 53% of them lost this geomorphological characteristic over 200 years (Piégay *et al.*, 2009). Although several reasons were put forward on why these braids have disappeared, embankments and modifications made to protect urban and agricultural areas have undoubtedly played a major role. The same study showed that of the braided rivers that were lost over a century, 21% had embankments, 48% were channelled and 5% were involved in dam constructions. In 1996, only 18% of rivers in the French Alps could be considered as wild hydrosystems (Pautou *et al.*, 1996). These changes in river morphology have had a significant impact on the vegetation associated with watercourses. The range of the dwarf bulrush (*Typha minima* Hoppe) was thus reduced by 85% in one century (Prunier *et al.*, 2010) and for the Isère river in Savoie, typical species of alpine braided streams saw the size of their habitat reduced by 90% due to bank containment (Girel, 2010).
- 3 Alpine stream embankments are often constructed of alluvial materials extracted from the river and generally overhang the riverbanks. They may have been protected from watercourse erosion by a hard covering or dry stone pitching, either in the form of stone masonry or concrete (more or less old), or as rip-rap. Rip-rap can sometimes be present only at the foot of riverbanks, but can equally cover the entire bank and facing on the river side of the embankment. These constructions are frequently colonized by woody vegetation, which colonizes gaps in between the rocks. This vegetation has matured over time, particularly following the Second World War, when maintenance was infrequent or abandoned completely.

Ecological role of riparian zones

- 4 Watercourses and their surrounding areas are found to have a naturally rich biodiversity. Many plant and animal species breed there, feed and hide there. They include areas at the interface (or ecotones) between terrestrial and aquatic environments and thus have a great wealth of flora and fauna. Although lakes and rivers occupy only 1-2% of the land surface, it is accepted that at least one third of vertebrates (fish, amphibians, reptiles, birds and mammals) are closely dependent on these environments to complete their life cycles (Lévêque, 1998). Riparian vegetation is also home to many terrestrial animals (mammals, birds, amphibians, arthropods, etc.), either present throughout their life cycle or only during part of the cycle, such as during reproduction or when searching for food.

- 5 In addition to the species dependent on riverbanks, riparian zones also host transitory groups of species. Riparian zones thus also play a major role as biological corridors and are used as migration corridors by many animal and plant species. These corridors perform essential ecological functions: by distributing propagules of many species from adjacent environments and providing continuity between zones that would otherwise often be fragmented, they increase the genetic diversity of populations and facilitate their mixing. This role is especially important in the Prealps where riparian zones sometimes constitute the last remaining ecological corridors available in the valleys, where building land is scarce and/or the other corridors have been destroyed by urbanization and infrastructure. On the Alpine scale, the importance of maintaining ecological networks is recognized as a major challenge in terms of maintaining a rich biodiversity (Kohler *et al.*, 2009).

The present article has three objectives:

- 6 1.Explain the paradox created when reinforced riverbanks are managed while seeking simultaneously to promote the safety of the embankments and the ecological functions of riparian zones.
- 7 2.Illustrate this conundrum through experiments carried out notably in the French and Swiss Prealps as part of the Gni'Alp project showing:
- The risks caused by the root systems of ligneous plants in the embankments;
 - The importance of revegetating the riverbanks to maintain biodiversity;
- 8 3.Make concrete management proposals that take into account these constraints.

The paradox of the management of riverbanks integrated in the engineered protective structures¹

- 9 Alpine riverbanks, when reinforced to protect against floods, are sometimes very close to or in contact with the embankment. Revegetating engineered embankments has many advantages from an ecological (Cavaill *et al.*, 2013), mechanical (Abernethy and Rutherford, 2001) and landscaping point of view. It is thus generally recommended to revegetate the embankments of watercourses, with woody plants, in particular.
- 10 However, when the riverbanks form part of or support backfill embankments, the use of woody plants can cause problems. Although, on the embankment *sensu stricto*, herbaceous vegetation is beneficial in that it effectively protects the slopes over the long term (from runoff, gullies), the presence of trees or shrubs can degrade the construction itself (Mriaux and Vennetier 2006; Vennetier *et al.*, 2003; Zanetti, 2010). These risks are linked to (i) the presence of the aerial parts of trees on the slope or at the bottom of the bank, making them susceptible to being blown over by the wind or ripped out by the current, and (ii) the root systems can create damage to the backfill or its foundations, by loosening the soil, breaking down some of the masonry and /or creating galleries resulting from decaying roots, which promote internal erosion (Zanetti *et al.*, 2010). These risks call into question the safety of such hydraulic structures and therefore the safety of people and properties located nearby. There may therefore be a contradiction between the desire to revegetate the banks of rivers using woody species, and the need to avoid the development of trees and shrubs on

embankments when the riverbank has been incorporated in the embankment structure. A detailed study is then required on a case by case basis.

- 11 In order to seek to remove this paradox concerning streams in the French prealps between promoting safety and biodiversity on the embankments of riverbanks, the Génî'Alp project has made it possible to carry out, simultaneously:
 - studies on the root development of ligneous plants in alpine river banks to better understand the associated risks;
 - Studies on the biodiversity of different types of riverbank to determine the impact on biodiversity of different types of river management.

Is it possible to ensure the safety of embankments and promote biodiversity when the riverbanks themselves serve as containment structures?

What is already known about vegetation in relation to the safe management of riverbank protection

- 12 The development of woody vegetation on embankments and riverbanks, especially the root systems of trees and shrubs has been the object of a detailed study in France (Zanetti, 2010). Nearly 300 adult trees were uprooted carefully to characterize the overall structure of their root systems (shape, size and direction of the roots and morphological characteristics), as well as the overall volume of the stumps (both "root system and materials (soil)").
- 13 As a follow-up to this study, with two experimental sites already involving embankments built on Alpine watercourses (embankments on the Isère upstream from Grenoble and the construction closing off the Casterino dam in the Maritime Alps), a specific experiment was conducted in 2011 as part of the Génî'Alp project on improving the embankments of the Leysse in the Savoie, with the support of Chambéry Metropole.
- 14 To characterize the rooting of ligneous species present on riverbanks and embankments in the Alpine region, an uprooting operation was carried out. Willows and alders were found to have a small creeping footprint (1 to 2.5 m³) when located in a riverbank, while having mixed or fasciculated root systems taking up a larger volume (4 to 8 m³) when located on the embankment. These observations were used to amend the recommendations for plant engineering techniques on a river bank close to an artificial embankment.
- 15 These experiments in alpine rivers confirmed the results obtained in the context of the large study previously cited, which showed that woody plants growing on embankments in temperate regions may have four types of roots: creeping, fasciculated, taproots and mixed (Köstler *et al.*, 1968). Each type creates different risks for embankments over the medium and long term (Zanetti *et al.*, 2010; Zanetti, 2010; Zanetti *et al.*, 2013).
- 16 A creeping system, when all the roots are superficial, is not very resistant to being ripped out, but on the hand, provides good anchoring of the soil surface faced with runoff or water current. This type of structure is dangerous if the roots travel through part of the structure, or when uprooted by the wind.

- 17 A fasciculated system has good resistance to being pulled out due to the dense and even distribution of roots in all directions, but it has a great overall volume, harmful to the structure in case of root rot or pulling out.
- 18 A taproot system usually has one or more large vertical roots (tap roots). These provide good anchorage for the tree, but they penetrate deep down into the body of the backfill by deconstructing it and risk collapse of the structure after the death of the tree when those big taproots rot down.
- 19 A root system consisting of a combination of horizontal and vertical roots, brings together the advantages and disadvantages outlined above for creeping roots and taproots.
- 20 The parameters influencing the structure of root systems are:
 - The material properties of the embankment or the riverbank
 - The position of the tree on the slope, which determines its access to water,
 - The plant species itself,
 - The age of the tree stump/root system.

Root structure and materials

- 21 The nature and the richness of the materials in which they grow play a key role in the organization of root systems. In coarse, draining and often poor materials (sand, gravel and stones), there are few roots, but they are usually rather large. They can be very long, because they are forced to penetrate large volumes of material to anchor the tree and find enough water. Conversely, in finer materials with a high proportion of silt or clay, which are richer and better at retaining water, the roots are more numerous, finer and usually shorter because they can find sufficient resources in a smaller volume.

Root structure and position of the tree on the embankment or riverbank

- 22 The structure of root systems also depends heavily on access to water. Trees growing at the bottom of the riverbank or embankment will have creeping root systems when the water table is near the surface. A flat root system is then observed on a plane that follows the top of the water table. Indeed, most species found along streams require significant amounts of water to grow, but they do not send roots below the normal water level (asphyxia), with the exception of some species of the *Alnus* genera (Armstrong and Armstrong, 2005) and probably *Platanus* and *Salix*.

Root structure and species

- 23 It has thus been shown that root structure depends much more on development conditions (access to water and nature of the materials) than on the plant species itself. However, some species have morphological characteristics that make them undesirable on embankments, including the ability to make some particularly large or long roots (Figure 1), likely to cross from one side of the structure to the other. This is particularly true of the black poplar (*Populus nigra* L.) and white poplar (*Populus alba* L.), white willow (*Salix alba* L.) and black locust (*Robinia pseudoacacia* L.). Arboreal poplars and willows are also able to send down large taproots when they can obtain water at depth, which generates a localized risk of collapse of the bank after the tree dies and the stump/root system have rotted away. These species (poplar, locust and willow) are

unfortunately very common on embankments. The introduction of these species must therefore be avoided at all costs on new or rebuilt embankments.

Figure 1. Large, long, creeping root of white willow at the bottom of a riverbank

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Root structure and age/tree root dimensions

- 24 For all species and for all types of root structure, there is very little relationship between the age of a tree and the space taken up by its root system. Differences in the site, the materials involved, the species and type of tree (as a shoot or from seed) can explain these variations. For specimens of equivalent age and under similar growing conditions (in the middle or high on the embankment or riverbank), the root systems of white willow and black or white poplar take up twice as much space as that of black locust or ash.

Biodiversity assessment based on the type of riverbank

- 25 In general, riverbank protection structures are of two types: civil engineering works consisting of stone masonry or concrete, gabion baskets or riprap; and bioengineering works made of living plants, making use of the biological, physiological and physical abilities of these plants to protect riverbanks against erosion (Frossard and Evette, 2009). There are also composite structures that combine both civil engineering and bioengineering. Bioengineering constructs integrate better with the landscape and their ecological environment than purely civil engineering works. Over time, a successful bioengineering structure becomes very close to a “natural” riverbank.
- 26 In the context of the Géni’Alp project, a quantitative ecological study on biodiversity on artificial river embankments was conducted in 2010 and 2011 on more than 30 structures in the Prealps (Rhône-Alpes and Switzerland). This study compared the biodiversity of riprap, bioengineering and natural willow. All the protective structures

were of a similar age (3-8 years). Data covered plants and ground beetles, but also benthic macroinvertebrates present in the submerged parts of the riverbank.

Figure 2. Comparing the average diversity in the number of plant species and the number of taxa for ground beetles and benthic macroinvertebrates found on civil engineering and bioengineering constructions and natural riverbanks.

ERROR BARS REPRESENT STANDARD ERRORS AND THE DIFFERENT LETTERS (A, B) INDICATE STATISTICALLY SIGNIFICANT DIFFERENCES.

- 27 Figure 2 shows that these thirty structures using bioengineering techniques – though recent – house a significantly higher diversity of plant species, approaching that found in natural riverbanks. However, statistical tests revealed no significant difference for ground beetles or for benthic macroinvertebrates, although they tended to increase along the gradient to a more natural environment. This suggests that adding vegetation to the riverbank encourages a better return to a functioning ecology compared to using rip-rap, both above and below the waterline.
- 28 These combined results tend to confirm that the materials used for riverbank constructions significantly influence the quality of riparian habitats and as a consequence, the populations of organisms that establish themselves there. Structures using bioengineering techniques promote more plant and animal diversity than those using civil engineering.

Development of invasive alien species on alpine streams and the importance of ligneous plants to limit their development

- 29 Riparian areas are particularly affected by invasions by alien species. Whether introduced intentionally or not, these plant species mainly from Asia and America have managed to spread and develop dramatically along European rivers. Very dynamic and for the most part heliophytes, they often take advantage of plant thinning or deforestation, carried out during embankment work, to establish themselves and spread.
- 30 Alpine massifs have not been spared, even if invasive alien species remain largely confined to disturbed areas and low altitudes (Dainese *et al.*, 2013). Thus, Asian

knotweeds (*Fallopia* ssp.) butterfly bush (*Buddleia davidii* Franch) or Himalayan balsam (*Impatiens glandulifera* Royle), among others, are spreading fast along rivers in the Prealps. Their development can severely affect the local flora and fauna. This raises strong management and planning issues. In addition to their impact on local biodiversity and the landscape, invasive alien species could weaken riverbanks *vis-à-vis* erosion, especially during winter (Dawson, Holland, 1999). Moreover, when embankments have been constructed, access to riverbanks or river-side slopes becomes more difficult and the visual monitoring of embankments is hampered by the development of the aerial parts of these vigorous species.

- 31 One of the major areas of research in invasion ecology is concerned with deciphering why certain areas are particularly susceptible to invasions. Among the mechanisms suggested is the major role played by the competitive ability of the plant community in place (Levine *et al.*, 2004). The more species are complementary in the spatial and temporal use of resources, the less they allow invasive alien species to use these resources to take over the area. At a local level, the presence of a competitive and functionally diverse plant community can reduce the performance of invasive alien species (Hooper, Dukes, 2010). In terms of management, these findings are translated into actions aimed at maintaining and restoring structured plant communities mainly comprised of tree and shrub species in riparian areas most at risk of invasion.
- 32 Paradoxically, in places, the safest short-term management practice for embankments, i.e. eliminating tree cover, can cause an explosion of invasive heliophiles that are normally kept under control and fairly dispersed by the shady conditions. Forming dense high mats (3-5 m), some of these (*Buddleia*, *Fallopia*) prevent the visual inspection of the slope and can be just as annoying as the original vegetation. It is therefore important to avoid the sudden clearing of areas where these invasive species are already present, and to provide an appropriate management plan where tree clearance cannot be avoided.

Vegetation recommended for use when the riverbanks are integrated into an embankment

Rules to be applied to embankments

- 33 Embankments function to protect property and people against floods, their proper functioning (performance, in terms of civil engineering) is therefore a priority if protection issues warrant it. To fulfil this vital security role, it is necessary to avoid all risks that may affect their seal or stability in any way, especially those related to the development of large root systems. Furthermore, in order to check the status of these embankments over time, it is essential to be able to monitor them regularly. Such visual inspections are unfortunately not compatible with the presence of dense woody or herbaceous growth, especially invasive species, which can hide potential problems. Besides, the presence of tree cover encourages the presence of large burrowing animals (badger, coypu, muskrat, etc.) that dig their burrows in embankments or their foundations (Mériaux *et al.*, 2004). Except in special cases, a dense low herbaceous cover, maintained by regular cutting is the best plant cover recommended to maintain both the protection and safety of the slopes of embankments.

Steps to take on a case by case basis

- 34 It is still difficult, however, to establish general rules for all riverside constructions and watercourses. In fact, each case is unique in terms of the size, history and materials used for the embankment structure, as well as the safety, social, ecological and landscape issues, and in terms of the hydrology, type, violence and frequency of flooding, local climate, position of the embankment with respect to the riverbank, safety margins, etc.
- 35 An accurate diagnosis and appropriate management plan are needed for any situation or choice made that deviates from the basic rule of avoiding the presence or installation of all ligneous plants on embankments and other river protection measures using backfill and to maintain a low herbaceous vegetation by regular cutting. This rule should only be departed from when considering very large widths with gentle slopes or constructions with sealed internal barriers made of hard material (moulded concrete, sheet pile). Even in these favourable cases, some minimum requirements are necessary, at least to allow for careful monitoring.
- 36 When riverbank protective structures are already forested, a frequent occurrence, at least these trees and their root systems should not be allowed to reach a great height or diameter and, pending a thorough diagnosis² and reinforcement work, regular clearing should be maintained between the trees in order to restore proper monitoring conditions. It should be noted that on river protection, structures with narrow and steep slopes, trees are sometimes the only elements providing some temporary stability to the structure. Removing them implies complete restoration of the structure from scratch.
- 37 Although it is sometimes difficult to accept from a social, ecological and landscape point of view, planting trees is not recommended, except as noted above (very wide banks or with inner sealed layer) on river embankments *on new ground or after restoration work*.
However, at distances of approximately 5 meters back from the foot of the embankment (limiting root colonization), developers are given free rein to install trees or shrubs as part of a landscaping plan and /or to compensate for the impact resulting from managing the embankment as a grass-only space (Figure 3). Advantage can also be made of this 5-meter strip on either side at the foot of the embankment to create a passageway for the periodic movement of maintenance and mowing equipment (service track).

Figure 3. Diagram summarizing the management procedures for woody plants on embankments

WHEN THE DISTANCE IS > 5 M, THE RIVERBANK CAN BE CONSIDERED AS NO LONGER FORMING PART OF THE EMBANKMENT AND SO THERE ARE NO LONGER ANY RESTRICTIONS ON THE CHOICE OF VEGETATION FOR THIS RIVERBANK

- 38 Finally, in embankment redevelopment projects, an interesting way of “reconciling” bioengineered embankments (without any restrictions) with the safety of the embankment when upgraded is to move the embankment, i.e. away from the river, on the sections where this is possible. Such solutions are now being undertaken in France (Rhône, Vidourle, Doubs, l’Agly, Isère, etc.,) and several such improvements that have been carried out or planned were presented at the recent 2013Dyke Colloquium in Aix-en-Provence (Salmi *et al.*, 2013). It goes without saying that the river and its ecosystem also gain from such development, recovering a little of its natural aspect.

General rules on revegetating alpine areas

- 39 It is generally preferable to use local ecotypes and species when revegetating alpine areas. These are generally best adapted to this environment. In addition, these mountain areas often have a typical local flora and diverse vegetation consisting of specific species or ecotypes. The use of local strains thus appears essential, both in the aim of using endemic plants adapted to local environmental conditions, and to respect the local plant history of these highly typical environments (Bonin *et al.*, 2013)
- 40 Survival of the species used for adding plant cover guarantees the good performance of the bioengineering work. This species survival is largely determined by their being well adapted to the environment encountered. Whether these are ecological adaptations (tolerance to floods, light, nutrients, moisture, pH, etc.) or biogeographic (altitude, continentality, etc.), the species chosen must be suitably adapted (Evette *et al.*, 2012).
- 41 Finally, adding vegetation along the banks of streams in an alpine environment also requires taking into account a number of specific features, including the hydrological regime and vegetation period (Bonin *et al.*, 2013).

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NOTES

1. In this article, like the definition adopted in the Géni'Alp guide, the riverbank is regarded as incorporated into the containment structure when the top of the bank merges with the bottom on the river or torrent side of said containment structure, or is within 5 meters of it (see Figure 3).

2. A very high resolution aerial LiDAR survey can be a very useful contribution to such a diagnosis, and in particular to facilitate the mapping and characterization of woody vegetation in place (Vennetier et al., 2010, Mériaux et al., 2013).

ABSTRACTS

Rivers in the Prealps have undergone considerable embankment and channelization work over recent centuries. The current management of these embankments often excludes woody plants for safety reasons. However, alluvial vegetation and riparian zones can play important ecological roles by providing often very biodiverse environments and acting as biological corridors.

There is a paradox when managing these embankments between the security requirement to exclude woody plants and the ecological imperative to add vegetation. Experiments carried out under the Géni'Alp Interreg project in the French and Swiss Prealps have improved our knowledge of both risks to embankments by the root systems of ligneous plants and the impact of creating artificial riverbanks on biodiversity.

This article aims to explain this paradox in the light of the results of these experiments. It presents an analysis of the size and spatial extension of the root systems of trees and shrubs extracted from the riverbanks and the embankments of two alpine streams. It also compares the results of findings on the taxonomic diversity of vegetation and ground beetles, as well as the diversity of benthic macrofauna between three types of banks: riprap, bioengineered and 'natural'. Based on these elements, this paper explores the management tradeoffs faced by river maintenance engineers and offers suggestions on how to meet this dual challenge.

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Mots-clés: Biodiversity, embankment, invasive alien species, bioengineering, riparian, risks, alpine rivers

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