Afterword

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As the sciences of fluvial geomorphology and river ecology have progressed, we now better understand that alluvial river channel form and its complex habitats depend upon fluvial process, including periodic disturbance by floods. In place of traditional notions that *'stability'* was desirable in ecology, we now see that disturbance is not only inevitable in many systems, but essential to their regeneration and maintenance of biodiversity (Naiman et al. 2005). Channel dynamics, bank erosion, deposition, and recruitment of large wood to the channel are essential processes to create the complex and diverse channel habitats (Florsheim et al. 2008, Gurnell et al. 2002) and diverse floodplain habitats (Stanford et al. 2005) needed by many valued species. Thus, there is increasing recognition in the scientific literature that the greatest ecological diversity and richness occur in dynamic river systems, in which the floodplain is frequently inundated, and the channel can migrate, erode, and deposit, allowing for establishment of native riparian vegetation.

More restoration programs now emphasize restoration of dynamic fluvial process. To the extent that a river can be granted its space of freedom, along with an at least partially natural flow and sediment regime, the river can rearrange its bed and banks in a more complex form, supporting native species evolved in adaptation to these conditions. However, in light of the severe constraints imposed by their surroundings, it is often assumed that process cannot be restored in urban rivers, and that only cosmetic *'gardening'* projects are possible. While this constraint holds true for many densely urbanized settings, there are some urban contexts in which semi-natural fluvial processes can be restored to the river corridor, and with time, these processes can restore natural forms to the river. Similarly, restoration for ecological function is often seen as opposed to improving access for humans. However, this need not necessarily be the case, and finding opportunities to restore rivers to improve both ecological function and human use is one of the key challenges in urban river management in this century.

Flood risk is commonly managed by structural measures such as dikes, flood control reservoirs, and engineered channels, measures which usually negatively impact ecological function. However, with increasing interest in *'nature-based solutions'*, managers seek opportunities to manage floods while also improving ecological functions. By granting the river a corridor in which to convey floodwaters and where it can move freely, it may be possible to restore fluvial process while also reducing flood risk.

The book, «*Let the River run*» eloquently presents the underlying concepts behind the restoration of the Aire River, as well as insightful details about its implementation.

Erodible corridor and espace de liberté

River restoration in North America began earlier than in Europe, and adopted a paradigm of designing a stable, single-thread, meandering channel as the idealized goal in river restoration (Kondolf 2006). This approach - the imposition of fixed, idealized forms - reflected an earlier idea of *'restoration'*, rooted in concepts of ecosystem stability rather than dynamism. The fixing of river forms in place also was consistent with the goals of most riparian landowners, who commonly want to avoid erosion of their riverbanks. This paradigm has been adopted by some state and federal agencies, is required for compensatory mitigation projects under the US Clean Water Act in at least one state (North Carolina, USA), and has now spawned a vast mitigation banking industry, which churns out virtually identical symmetrical meandering channels – commodifying river 'restoration' as an industry in which large investment banks now have stakes (Lave et al 2008, Doyle et al. 2015, Lave and Doye 2021).

In contrast, river restoration trend started in Europe in the 1990s, and became widespread in response to requirements of the Water Framework Directive (European Commission 2000), which encouraged integration of more advanced concepts of fluvial process as a basis for ecosystem restoration, in effect leap-frogging over the 'stable-meandering-channel' paradigm still prevalent in much of North American practice. While there are many *'restoration'* projects in Europe that do not restore process, we find many more examples of true process restoration here (Habersack and Piegay 2010).

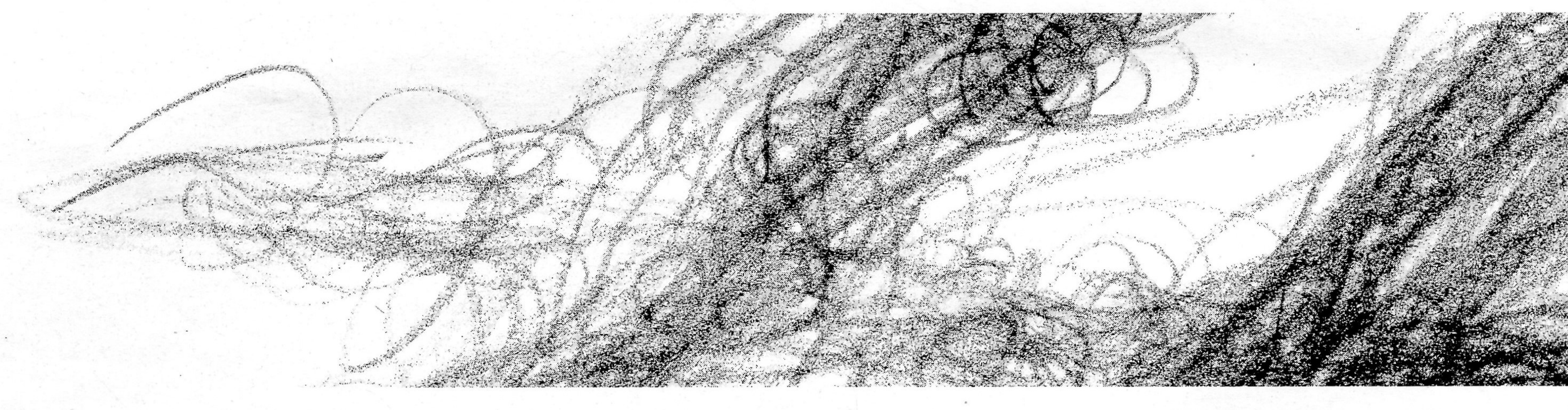
Given that dynamic fluvial processes create the complex habitats needed by native species, it follows that the most effective ecological strategy is to set aside a zone within which riverine processes can function without conflicting with human uses, termed variously the *'espace de liberté'*, *'erodible corridor'* (Piégay et al. 2005), *'fluvial territory'* (Ollero 2008), or *'channel migration zone'* (Rapp and Abbe 2003). This approach can be viewed as *'preservation'* of what's already working, and a more effective use of restoration funds than projects involving active intervention and physical changes to restore the channel. Where the river has sufficient stream power (to move sediment) and sufficient sediment load, the most sustainable restoration strategy will likely be to remove structures that constrain the river, and thereby let the river restore itself over subsequent years – to - decades through erosion, deposition, and development of riparian vegetation (Kondolf 2011)..

If it's too late to preserve a functioning river system, the next best is to restore process (Ciotti et al 2021, Beechie et al. 2010, Kondolf et al 2006). Examples include removing dikes that block floodwaters from inundating floodplains, removing hardened bank protection that prevents channel migration, restoring flow dynamics with high flows released from reservoirs, and restoring sediment dynamics by adding gravel to sediment-starved channels downstream of reservoirs. In these cases, by restoring the processes we allow the river to create complex forms (and thereby diverse habitats). By contrast, the least sustainable *'restoration'* approaches - and those least likely to succeed - are those that attempt to directly create, through mechanical action, the complex habitats of the natural river, especially if the restoration goals are based on outdated notions of stability as the desired ecosystem state. Without the processes that naturally create and maintain these geomorphic features and habitats, it is unlikely that the artificially constructed habitats will persist for long.

Process-Based Restoration

While many restoration project today are billed as *"process restoration"* or *"geomorphically-based restoration"*, some of these do not merit the title. As articulated by Ciotti et al. (2021), process restoration can be identified based on four criteria: space, energy, materials, and time.

Space. Removing constraints to overbank flooding and channel migration can allow river processes to operate over a larger area (increasing the process space), in turn creating the channel-floodplain complexity and connectivity that will support the desired ecology. Thus, the first criterion to apply to a restoration project is whether it increases the river's process space. The Aire River restoration increased the channel width from the 15-m width of the canal to the 100-m width of the espace de liberte created to the south. [However, the channel is now migrating into the southern boundary of the espace de liberté at two points, suggesting that the river may need more than the 100-m width given it by the project. Given the success of the project to date, an expansion of the river corridor to the south is now under consideration.] Moreover, the transverse dikes that



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impound floodwaters across the floodplain during large floods effectively increase the river's footprint across its floodplain, while providing important flood risk management benefits to densely urbanized downstream reaches.

Energy. Another key aspect of process restoration is the source of energy. Conventional channel reconstruction projects (such as those documented by Doyle et al. 2019 as required for compensatory mitigation in North Carolina, USA) use bulldozers, excavators, and other heavy equipment to construct the end product, the idealized channel form. These projects depend primarily on large inputs of fossil fuel energy, and the constructed channels must be fixed in place by large rocks to resist the erosive forces of floods. By contrast, process restoration depends to the extent possible on natural sources of energy, notably the river in flood, which erodes, deposits, and thereby rearranges the architecture of the channel and floodplain. Even frequent natural floods can exert considerable energy on the channel: a 5-year flood on a stream draining XX km2 can exert energy equivalent to about 50 days of bulldozer operation (Ciotti et al 2021). The direct energy of the sun drives plant growth, which contributes to the evolution of channel form, holding riverbanks together, and providing shade to river waters in summer, hydraulic roughness to the floodplain during overbank flows, leaf litter to the stream (an important allochthonous input to the stream's ecology), and large wood, which creates habitat complexity. In some settings, biomorphic power can include the effects of many organisms large and small, such as the mussels who filter fine sediment from the stream waters, and beavers, whose dams raise water tables and trap organic matter (Johnson et al 2019). On the Aire, heavy equipment was used to excavate the multiple channels, but by leaving the lozenges in place (in lieu of presumed lowering of the entire footprint of the restored channel), the fossil energy required to excavate and carry away material was minimized. Most importantly, the energy of the river in flood was harnessed to form the channels. Even a series of small floods, with return intervals less than 2 years were sufficient to initiate erosion of the lozenges and deposition of natural fluvial forms such as gravel bars. With the establishment of riparian vegetation over the past seven years, the evolving channel is now taking on a clear form, as the energy of the river flow interacts with the stabilizing effects of trees and other riparian plants.

Materials. Process restoration uses locally sourced materials that are geomorphically appropriate to the site, rather than overwhelming the channel with artificial elements that would not naturally occur at the site, such as importing large boulders into streams with finer-grained bed and banks to create immobile structures that fix a constructed channel in place and prevent channel migration. Instead, process restoration uses structures as short-term tools to accelerate beneficial biogeomorphic processes. The structures are not expected to persist without change through subsequent high flows (Ciotti et al 2021). Except for a few key sites (e.g., at infrastructure crossings), the banks of the Aire were not hardened with boulders or other elements imported from elsewhere. Rather, the banks were encouraged to erode and deposit in response to the river's flow patterns and the growth of riparian vegetation in and along the restored channel. The site naturally had a diversity of sediment sizes, from dense clays to large gravels and cobbles (owing to the legacy of glaciation). The evolution of the individual lozenges was influenced in large measure by their composition, the lozenges cut in clay being more resistant to erosion than those composed of gravel.

Time. One distinguishing feature of process-based restoration is that the objective is not to create an idealized river form directly, but rather the interventions are intended to induce the interaction of physical and biological processes to create naturally functioning fluvial ecosystems (Ciotti et al. 2021). The idea is to implement incremental, small interventions that subsequently direct the energy of high flows to restore channel complexity, and that allow riparian vegetation to establish. This prompted recovery (Downs and Gregory 2004) uses the natural energy of the river to accomplish the restoration objectives, but this takes time. A key innovation of the Aire project was its starting condition, i.e. the grid of channels cut and the lozenges that remained in between them. The pilot channels offered the Aire alternative paths from which to choose its course, and importantly, an abundant supply of sediment with which to build complex channel forms such as gravel bars and riffles, resulting in an acceleration of the channel evolution process. The accelerated channel evolution and visually interesting pattern of the lozenges were important attributes for creating public buy-in to the project in this very visible urban setting

The espace de liberté approach will not work everywhere. Some rivers are too constrained by encroachment of buildings and infrastructure upon river banks, leaving insufficient room for an active corridor. Some rivers have insufficient energy and sediment load, such that spontaneous recovery from channelization or other such impacts might take centuries, if it were to occur at all. Fortunately, the Aire was well suited to the approach. It was possible to regain some of the river's former corridor width from the agricultural lands to the south, giving the river more room to move. Moreover, it was clear that the Aire still experienced frequent geomorphically-competent flows, and that it had sufficient sediment supply to build complex channel forms, based on observed rates of sediment deposition in a sediment basin on the alluvial fan and in a pool excavated for fish habitat. Thus, the Aire had sufficient space, stream power and sediment load to re-create its channel.

conclusions

Letting the river restore itself through natural channel dynamics seems an obvious approach, both for the likely ultimate success of the restoration and for cost efficiency in achieving the result. While there are now multiple examples of such projects in Europe since adoption of the Water Framework Directive (European Commission 2000), they have mostly been in rural settings. The Aire illustrates a successful espace de liberté within an urbanized region. In this case, agricultural lands adjacent to the river channel were converted to river corridor, but in other cases parking lots, abandoned industrial parcels, or other land uses may offer opportunities to expand the width of the river's process space.

The Aire project provides a refreshing contrast to the dominant paradigm in North American river restoration of constructing stable, single-thread channels locked in place by boulders and other large elements. The desire to fix channels in place probably reflects popular misconceptions about fluvial geomorphology and aquatic ecology when stream restoration first became popular in North America, as well as underlying and unspoken cultural preferences for such channels (Kondolf 2006). The dynamic nature of the Aire River post-restoration provides an alternative restoration path, one more attuned with real river processes in lieu of idealized forms imposed on the river. As we understand better how fluvial ecosystems function, it is increasingly clear that the natural processes of erosion, sedimentation, and channel migration do a very good job of creating high quality habitat. The most effective approach to restoring rivers will often be for us to stand aside, and give the river its space.

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