

基于动态演变过程的城市河流修复： 以艾尔河与伊萨尔河为例

Restoring Dynamic Fluvial Processes in Urban Rivers: Learning from the Aire and Isar Rivers

G·马蒂亚斯·康道夫

加州大学伯克利分校环境设计学院景观设计与环境规划学教授

乔治·德贡布

捷克ADR建筑事务所景观设计师

奥德·赞格拉夫-哈梅德

德国慕尼黑工业大学生命科学学院策略性景观规划与管理系副研究员

G. Mathias KONDOLF*

Professor, Department of Landscape Architecture & Environmental Planning, College of Environmental Design, University of California, Berkeley

Georges DESCOMBES

Landscape Architect, Atelier Descombes Rampini SA

Aude ZINGRAFF-HAMED

Research Associate, Chair for Strategic Landscape Planning and Management, School of Life Science, Technical University of Munich

*Corresponding Author

Address: Department of Landscape Architecture & Environmental Planning, University of California, Berkeley, CA 94720, USA
Email: kondolf@berkeley.edu

翻译 | 冉玲于、张晨希、申瑞琪、闫露

TRANSLATED BY | RAN Lingyu, ZHANG Chenxi, SHEN Ruiqi, YAN Lu

摘要

过程修复的河流修复方法并非直接创造出复杂的河流形态，而是通过少量人工干预“促进”河流动态过程的发生，以促进其自愈。河流生态条件的改善实际上是借助洪水的冲击（水流的能量）和河岸植被的生长（太阳辐射的能量）来实现的。在日内瓦的艾尔河上，通过“还水以自由”，恢复了艾尔河被开凿为运河前的生态功能。在谷底挖掘出的沟渠网络允许河流自由地淹没土地、侵蚀河床与河岸，泥沙可在此淤积成堤坝，复杂的水生栖息地得以形成，丰富着河流生态系统的食物网。在沟渠网络之间突出的菱形岛屿随着河水流动而逐渐被侵蚀，最终演变成了复杂的河道形态。在慕尼黑伊萨尔河的修复策略中，利用粗泥沙将原有的固化驳岸替换为可侵蚀的河床和堤岸，预留出河流演变、侵蚀和淤积作用的空间，并重塑了8km长的可达河岸线。自修复策略实施以来，通过泥沙的自然输移过程形成了砾石滩，其形态又在洪水的冲击中发生着演变，孕育了多样的栖息地。这两个项目均满足了过程修复的4个评价指标——空间、能源、材料和时间——且都可展示出通过修复河流动态演变过程来修复城市河流，并实现生态和社会效益的可能性。

关键词

河流修复；城市河流；河流过程；过程修复；绩效评估；艾尔河；伊萨尔河

ABSTRACT

In process-based restoration, the objective is not to create a complex river form directly; instead, interventions are intended to “prompt” the natural processes to restore such forms. The improvements in ecological conditions are actually made over time by flowing water during floods (using the stream’s energy), and by the growth of riparian vegetation (using incoming solar energy). On the Aire River in Geneva, ecological function was restored to a formerly canalized river by providing the river with an *espace de liberté*. A grid of channels cut into the valley bottom allowed the river to freely flood, erode its bed and banks, and deposit bars, creating complex surfaces on which riparian vegetation established to support the food web of the riverine ecosystem. The diamond-shaped bits of land left between these channels (“lozenges”) gradually erode and evolve as the river migrates, creating complex channel forms. The Isar River in Munich restoration involved adding coarse sediment load, creating erodible bed and banks in place of formerly rigid boundaries, expanding process space for river migration, erosion, and deposition, and increased human access to the river over 8 km. Since restoration, natural transport of sediment has resulted in deposition of gravel bars, whose forms evolve during floods, supporting diverse habitats. The Isar and Aire Rivers provide compelling examples of process-based restoration meeting 4 criteria for process-based restoration: space, energy, materials, and time. They demonstrate the possibilities of urban river restoration to achieve both ecological and social goals through restoration of fluvial process.

KEYWORDS

River Restoration; Urban River; River Process; Process-Based Restoration; Performance Evaluation; The Aire River; The Isar River

1 引言

随着河流地貌学与河流生态学的发展,人们已逐渐认识到冲积河道形态与河床演变之间的密切关系。“扰动”不只是众多生态系统的天然特征,更对系统更新与生物多样性的维持具有重要意义——这一观念正在取代过去追求“稳定”的传统观念^[1]。河道动力、河岸侵蚀与淤积作用和大型木材补给被认为是构建复杂多样的河道^{[2][3]}与河漫滩栖息地^[4]的重要要素,而这些栖息地又可成为许多珍贵物种的生存场所。同时也有越来越多的研究发现,生态多样性与物种丰富度最高的地方往往出现在具有动态变化的河流系统中,在这些系统中,河漫滩可定期被淹没,河道会进行泥沙输移、侵蚀和淤积等活动,并可为本地河岸植被群落的建立提供必要条件^{[5][6]}。

此外,越来越多的修复项目开始重视河流动态演变过程^[7]。当河流拥有可以自由流动的空间和至少处于半自然状态的水流与泥沙时,便可以实现自我修复,演变出更为复杂的河床与河岸形态,从而支持已适应此类环境的本地物种的生长。然而,由于上述条件在人居环境中的严重缺失,人们往往认为河流并不能恢复到这种理想状态,而只能实施一些装饰性的“园艺”项目——在许多高度城市化的地区,情况确实如此。但是,在其他一些城市环境中,仍然可以通过修复至半自然状态的河流演变过程,以及预留充足时间,使其逐渐恢复到自然形态。另外,修复生态功能与提升公众使用体验常被认为互相矛盾^[8],事实上二者是可以兼顾的——这是对21世纪的城市河流管理的一个挑战,亦是一次难得的机遇。

洪水风险管理常常需要利用堤坝、水库、人工水渠等灰色基础设施,但这些设施在一定程度上会损害河流的生态功能。随着“基于自然的解决方案”(Nature-Based Solutions)概念的出现,相关部门开始寻求可以兼顾洪水调控与生态功能改善的方法——提供允许洪水自由、安全通过的廊道空间,就有可能在降低洪水风险的同时,修复河流动态演变过程。

本研究从修复演变过程的角度出发,通过对位于瑞士日内瓦城郊的艾尔河和位于德国慕尼黑市中心的伊萨尔河两个城市河流修复项目进行绩效评估,探究在何种程度下,河流动态修复既能适应人类使用,又能实现城市洪水有效管理的目标。

2 河流修复的发展与“还水以自由”理念

北美的河流修复实践开始较早,他们多将稳定、单线的蜿蜒河道作为理想的修复目标^[9]。这种强干预的方法体现了早期河流修复的思路,

1 Introduction

As the sciences of fluvial geomorphology and river ecology have progressed, the dependence of alluvial river channel form upon fluvial process has become better understood. In place of traditional notions that “stability” was desirable in ecology, there is an increasing recognition that disturbance is not only inevitable in many systems, but also essential to their regeneration and maintenance of biodiversity^[1]. Channel dynamics, bank erosion, deposition, and recruitment of large wood to the channel are now understood to be essential processes to create complex and diverse channel habitats^{[2][3]} and floodplain habitats^[4] needed by many valued species. Thus, there is an increasing recognition in scientific literature that the greatest ecological diversity and richness occur in dynamic river systems, where the floodplain is frequently inundated, and the channel can migrate, erode, and deposit, allowing for establishment of native riparian vegetation^{[5][6]}.

More restoration programs now emphasize restoration of dynamic fluvial process^[7]. 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 into 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 holds true for many densely urbanized settings, there are some urban contexts where semi-natural fluvial processes can be restored to the river corridor, and with time, these processes can restore the river into natural forms. Similarly, restoration for ecological function is often seen as opposed to improving use for humans^[8]. However, this needs not always be the case, and finding opportunities to achieve the two goals is both a key challenge and a rare opportunity in contemporary urban river management.

Flood risk is commonly managed by structural measures such as dikes, reservoirs, and engineered channels, which usually negatively impact ecological functions. 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 to convey floodwaters freely, it may be possible to restore fluvial process as well as reduce flood risk.

In this paper, we consider two urban river restoration projects from the perspective of process restoration, assessing the degree to restore fluvial process for human use, while also effectively managing floodwaters within a peri-urban setting (the Aire River, Geneva, Switzerland) and a central urban setting (the Isar River, Munich, Germany).

2 Evolution of River Restoration and the *Espace de Liberté*

River restoration practice in North America began earlier than in Europe, and adopted a paradigm of designing a stable, single-thread, and meandering channel

该方法可溯源至生态系统稳定性（而非动态性）的概念。这种将河流禁锢于固化河道中的修复模式与大多数河岸土地所有者希望避免河岸侵蚀的目标不谋而合。该模式已被美国的一些州和联邦机构采用，且北卡罗来纳州已根据《清洁水法》制定了需遵循此模式的“损害补偿方案”。而这催生出了一个庞大的补偿银行产业，大型投资银行将这种批量建造的均质的蜿蜒河道产业化，以作持股^{[10]-[12]}。而地貌学家和生态学家则指出，这些所谓的蜿蜒河道和固化的封闭河岸与河流动态过程的自然规律相悖^[9]。

而欧洲的河流修复实践多始于20世纪90年代。最著名的项目当属埃姆舍尔河的修复，这条位于工业化程度极高的鲁尔山谷中的河流一度被渠化为排水明沟^[13]。为响应2000年正式实行的《欧盟水框架指令》的要求^[14]，人们引入了更加先进的河流演变过程概念，并将其作为河流生态系统修复的理论基础，基于此理论的河流修复实践逐渐在欧洲推广开来——这已超越了北美某些项目中仍在使用的“稳定的蜿蜒河道”的修复模式。今天的欧洲虽然仍在进行很多留于表面的“修复”工程，但基于河流动态过程的实践案例也正如雨后春笋般涌现^[7]。

为动态的河流演变留出空间，避免人类活动干扰，从而允许河流自行营造本地物种所需的复杂栖息地应当是最有效的生态修复方法。目前，研究人员将这种空间称为“还水以自由（的空间）”^[15]、“可侵蚀廊道”^[16]、“流动领地”^[17]、“河道迁移带”^[18]等。通过选择保护河流演变过程，而非采取主动干预和固化驳岸的措施来修复河流，可实现修复资金最高的成本效益。对于具备足够的水流挟沙能力和含沙量的河段，可实施的最具可持续性的修复策略是拆除影响河流运动的构筑物（如阻止洪水漫溢的堤坝和阻止河道迁移的固化驳岸等），可允许河流侵蚀与淤积活动的进行，并为植被群落重建创造条件，最终实现河流自愈^{[6][19]-[21]}。

下一步的最有效措施是恢复河流动态演变过程。比如可利用河流上游水库来释放大量水流，以在下游模拟出洪水冲刷的效果，从而恢复水流动力；或在缺乏沉积物的河道中添加碎石，从而恢复泥沙动力。借助此类途径，可逐步恢复河流的复杂形态、创造多样的栖息地。^{[19]-[21]}与之相反，河流修复时最不可取的方法就是试图通过工程措施直接建设自然河流才会拥有的复杂栖息地，尤其是当修复目标还停留在“修复至稳

as the idealized goal in river restoration^[9]. This approach—the imposition of fixed and 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 riverbank erosion. This paradigm has been adopted by some state and federal agencies in the United States, wherein at least one state (North Carolina) stipulates that compensatory mitigation projects under the Clean Water Act must follow this paradigm. Now, a vast mitigation banking industry is spawned, which churns out virtually identical symmetrical meandering channels—commodifying river “restoration” as an industry in which large investment banks now have stakes^{[10]-[12]}. These meandering channels with their locked-in banks have come under criticism from geomorphologists and ecologists who point out the conflict between fixed banks and dynamic river processes^[9].

In contrast, river restoration practice started in Europe in the 1990s, with the best known project probably being the emblematic restoration of the Emscher River in the industrialized Ruhr Valley, which had been a canalized open sewer^[13]. As river restoration became widespread in Europe after 2000 in response to requirements of the Water Framework Directive^[14], the field has integrated more advanced concepts of fluvial process as a basis for ecosystem restoration, in effect leap-frogging over the “stable-meandering-channel” paradigm in which much of North American practice is still mired. While there are many “restoration” projects in Europe that do not restore process, we find many more examples of true process restoration here^[7].

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* (or space of liberty)”^[15], “erodible corridor”^[16], “fluvial territory”^[17], “channel migration zone”^[18], etc. This approach can be viewed as “preservation” of what has already been 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^[6]. Examples include removing dikes that block floodwaters from inundating floodplains and removing hardened bank protection that prevents channel migration^{[19]-[21]}.

The next most effective strategy would be restoration of processes. Downstream of reservoirs, this could include restoring flow dynamics with deliberate high flow releases to mimic the effects of floods and restoring sediment dynamics by adding gravels to sediment-starved channels. In these cases, restoring the processes allows the rivers to create complex forms (and thereby diverse habitats).^{[19]-[21]} By contrast, the least sustainable “restoration” approaches—and those least likely to succeed—are those that attempt to directly create, through

定的理想水生态系统状态”的陈旧理念上时。如果河流动态过程已遭到破坏，无法再遵从自然规律创造并维持河流的地貌特征和栖息地环境，人工建造的栖息地也将无法持续。

3 过程修复的评估指标

尽管目前许多修复项目都宣称自己是“过程修复”或“基于地貌的修复”，但部分项目却是有名无实。判断项目能否真的可被称为“过程修复” / “还水以自由”，可以参考达米恩·乔蒂等人提出的4个指标：空间、能源、材料和时间^[19]。

3.1 空间

如上所述，通过减少对溢岸泛滥和河道迁移活动在结构上的束缚，河流将在更大的区域 / “动态演变过程空间”中流动，河流的动态演变过程又会促进形成河道 - 河漫滩复杂的形态、增加水系的连通性，进而营造出理想的生态系统。因此，可称之为“过程修复”的工程的首要标准是：是否运用后退、破口、拆除堤坝和清除水流障碍物等措施来扩大河流动态演变过程所需的空間。乔蒂等人研究了流域面积为62km²的加州多蒂峡谷生态修复过程，发现通过拆除防洪堤坝，这段长达700m的土地重新成为了河流的一部分；河流动态演变空间的宽度从80m以下恢复到了200~400m之间，面积从3hm²增加到了23hm²^[19]。

3.2 能源

判断过程修复的另一个重要指标是能源。传统的河道重建项目（如2015年马丁·W·多伊尔等人根据美国北卡罗来纳州的损害补偿方案整理的相关项目）多使用推土机、挖掘机和其他重型设备直接塑造理想的渠道形态，而这些河道必须使用大块岩石来固化，以抵御洪水的侵蚀力^[11]——因此，这些项目主要依赖大量的化石能源。相较而言，过程修复则更加依赖于自然能源，尤其是洪水期间的河流动力，可以加速河道的侵蚀和淤积作用，进而重新布局河道与河漫滩。即便是低重现期的自然洪水的冲击也会给河道带来很大的改变，例如，多蒂峡谷中5年一遇的洪水所带来的能量相当于推土机作业近50天^[19]。此外，太阳辐射产生的能量会促进植被生长，进而推动河道形态的演变——这些植被亦能固定河岸；在炎炎夏日时荫蔽河水；又能在洪水在河漫滩蔓延时增加阻力；植被的枯枝落叶可成为溪流生态系统重要的外部能量来源；落入河道的大型木材则会增加栖息地的复杂性。也可以借助其他生物提供的能

mechanical actions, 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.

3 Criteria for Process-Based Restoration

While many restoration projects today are billed as “process restoration” or “geomorphically-based restoration,” some of these do not merit the title. As articulated by Damion Ciotti et al., process-based restoration/*espace de liberté* can be identified in terms of four criteria: space, energy, materials, and time^[19].

3.1 Space

As noted above, 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, through actions such as setting back, breaching, or removing dikes, and removing obstructions to flow. Ciotti et al. presented the example of Doty Ravine in California (drainage area 62 km²), where flood control dikes were removed, allowing the stream to rework most of its bottomland over a length of 700 m. The width of the active stream corridor increased from less than 80 m to between 200 m and 400 m, which increased the process space from 3 hm² to 23 hm².^[19]

3.2 Energy

Another key aspect of process restoration is the source of energy. Conventional channel reconstruction projects (such as those documented by Doyle et al. 2015 as required for compensatory mitigation in North Carolina, USA) use bulldozers, excavators, and other heavy equipments to construct the end product—the idealized channel form, and the constructed channels must be fixed in place by large rocks to resist the erosive forces of floods^[11]. Thus, these projects depend primarily on large inputs of fossil fuel energy. By contrast, process restoration depends to the extent possible on natural sources of energy. The most important is the energy of 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. For example, a 5-year flood on Doty Ravine exerts energy equivalent to about 50 days of bulldozer operation^[19]. In addition, the direct energy of the sun drives plant growth, which contributes to the evolution of channel form, holding riverbanks together, providing shade to river waters in summer time, providing hydraulic roughness to the floodplain during overbank flows, contributing leaf litter to the stream—an important allochthonous input to the stream’s ecology, and providing large wood

源进行过程修复——如河狸通过修筑堤坝来抬高水位并储存食物，贻贝会过滤水中的细颗粒泥沙——这都可以被称作“生物形态的修复力量”^[22]。

3.3 材料

过程修复应使用适配于场地地貌的本地材料，而非大量引入场地中没有的人工元素，比如在多为细沙的河床和河岸中使用大块石材来稳固堤岸和防止河道迁移是不可取的方法。相反，可借助一些可以适应高流量环境的临时结构（如圆木，其可在短期内引导水流、增强栖息地功能；但随着时间推移，圆木将被微生物分解而消失）来加速有益的生物地貌演变过程^[19]。

3.4 时间

过程修复的另一个显著特征是：修复目的并非直接创建一个理想的河流形态，而是要促进河流中物理过程和生物过程的相互作用，以创建一个可自行运转的河流生态系统^[19]。具体而言，就是逐步实施低干预措施引导具有强大动能的水流，恢复河道复杂性、促进河岸植被群落的重建。这种修复方法鼓励利用河流自身的能量来实现修复目标，但这一过程需要充足时间^[23]。美国加利福尼亚州的鹿溪曾因实施防洪措施导致河道简化拉直，在防洪堤坝拆除后，研究人员通过监测经历一次5年一遇洪水后的河道地貌变化，发现大约经历8次这样的洪水事件（即40年左右）便可实现河道的重新布局，使河流基本恢复到实施防洪干预之前的自然状态^[15]。因此，在过程修复中，（旨在影响河流动态演变过程的）修复措施与预期的河道变化之间通常会有延迟——河流生态条件的改善实际上是借助洪水期的水流动能和（源自太阳辐射能量的）河岸植被的生长来实现的。

4 过程修复的制约因素

“过程修复” / “还水以自由”的修复方法主要受到两大因素的限制：1) 建筑和基础设施侵占河岸土地，导致河流缺乏充足的自由流动空间；2) 水流动力和输沙量不足，导致河流从渠化状态恢复到自然状态的时间过长（可能需要几个世纪）。图1展示了这两大因素对有效实施“还水以自由”修复方法的潜在影响：有效实施这一修复方法对河流及其周边环境的要求是城市对河流近岸的侵占相对较少，且具备充足的水流动力和输沙量（图1右上角）。相反，若水流动力和泥沙淤积程度

that falls into the channel and provides habitat complexity. In addition, process restoration could harness other biological sources of energy, such as the energy of beavers who build dams, a form of “biomorphic power,” to raise water tables and trap organic matter, and the mussels who filter fine sediment from the stream waters^[22].

3.3 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. An example would be artificial log structures that will serve to direct river energy but which are expected to deteriorate over time. Under a process restoration approach, structures are not expected to persist without change through subsequent high flows^[19].

3.4 Time

One distinguishing feature of process-based restoration is that the objective is not to create an idealized river form directly, but rather to induce the interaction of physical and biological processes to create naturally functioning fluvial ecosystems^[19]. 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 uses the natural energy of the river to accomplish the restoration objectives, but this takes time^[23]. Geomorphic monitoring of channel changes after a 5-year flood on Deer Creek in California, the United States suggested that about eight such events would be sufficient to rearrange the channel to resemble its complex natural state prior to flood-control interventions that simplified and straightened the stream. This implied that the system would take about four decades to recover after flood control dikes were set back.^[15] Thus, in process-based restoration there is commonly a delay between the restoration actions (designed to influence the fluvial processes) and the intended channel changes. The improvements in ecological conditions of the river are actually made over time by flowing water during floods (using the stream's energy), and by the growth of riparian vegetation (using incoming solar energy).

4 Constraints on Process-Based Restoration

The process-based restoration/*espace de liberté* approach can be constrained by 1) encroachment of buildings and infrastructures upon river banks, leaving insufficient room for an active corridor, or 2) insufficient energy and sediment load, such that spontaneous recovery from channelization or other such impacts

均较低，无论自然条件或人为干预如何改变，河流均无法形成侵蚀和泥沙淤积作用，更不用说重塑复杂的河流形态（图1右下角）——至少在常见的河流修复项目中，从施工到修复效果显现出来的时间范围内是无法完成的。^[15]

对于水库下游河道，可通过上游水库的流量调节和淤积泥沙转移来调整水流动力和输沙量以实现部分修复（图1中部）。然而当河岸周边已高度城市化时，为了抵御河水侵蚀和防止城市基础设施损坏，通常

1. “还水以自由”方法与其他较强干预的河流管理方法的适用性比较：x轴代表城市侵占河岸空间的程度，y轴代表水流动力与输沙量（来源：参考文献[17]）。
1. The suitability of the *espace de liberté* vs. other more intrusive river management approaches, as a function of degree of urban encroachment (x-axis) and available stream power and sediment load (y-axis) [Source: Ref. [17]].

might take centuries, if it were to occur at all. The effects of these two factors on the potential for effective implementation of the *espace de liberté* approach are shown in Figure 1. The greatest potential for the approach is in the upper right corner of the bivariate plot, where there is relatively little urban encroachment up to the banks, and stream power and sediment load are high. Where stream power and sediment load are low, whether the condition be natural (reflecting catchment geomorphology) or resulting from human-induced changes (such as reservoir-reduced flow regime and sediment load), the river does not have the capacity to erode, deposit, or rebuild its complex forms (lower right corner of Figure 1), at least not on time scales typically demanded by the public for visible restoration projects.^[15]

Downstream of dams, flow dynamics and sediment loads can be partially restored through reservoir reoperation and sediment augmentation (center of Figure 1). However, high stream power and sediment load are not sufficient in themselves, because even a potentially dynamic channel could not be permitted to



会加固河道。此时，无论拥有多大的水流动力和输沙量，这些河流都无法发生侵蚀、泥沙淤积和输移作用，只能在修复方案中纳入部分自然元素（图1左上角）。在高度城市化环境中，对这些水流动力和输沙量均较低的河流所进行的修复工作只能称为是在已被拉直或渠化的河流上的“园艺装饰”，它们往往会附带一些休闲设施，但都与河流动态演变过程没有关联，并且常需人工维护（图1左下角）^[6]——在这种环境下，河流的社会效益可能比生态效益更重要。

城市河流的这种局限性与可能性在艾尔河和伊萨尔河的修复案例中得到了展示——两条河流的动态演变过程空间均得到了有限扩大。且都是近10年来的建成项目（目前，艾尔河的四期河段仍处在最终施工阶段），且处在大型城市中：其中，艾尔河位于城市边缘地带，位于一个特别为农业生产而划分出的农田保护区，如今已完全被城市建成环境所包围，就好像是日内瓦的“中央公园”；而伊萨尔河则直接穿过了慕尼黑的市中心。两条河流都流经阿尔卑斯山脉，拥有足够的水流动能来修复河道——尤其是伊萨尔河，正是河水的自由流动促使其地貌演变过程恢复了活力。

5 日内瓦艾尔河：一条城市边缘地带的河流

曾被开凿为运河的艾尔河通过“还水以自由”方法，修复了自然状态下的生态功能。水流可在此自由地淹没河岸、侵蚀河床，泥沙可淤积为堤坝。在这些水流作用下，营造出复杂的水生栖息地和滨河廊道，并形成了复杂的河流生态系统食物网。

5.1 背景

艾尔河发源于法国阿尔卑斯山脉中的萨雷布山，向北流经冰碛，进入日内瓦西南部宽阔的艾尔平原后，开始自由流淌、冲积，形成了面积约为100km²的艾尔河流域（图2）^[15]。起初，艾尔河的平面形态为辫状型，在穿越冲积扇后过渡为单股弯曲线型（弯曲率为1.46），而后向东流至阿尔沃河（图3）。这条河流始终保持着自然形态，直到19世纪末20世纪初，为了改善排水系统、提升排洪效率，原本长约3km的蜿蜒河道被人为拉直渠化，改造成有着混凝土堤岸和梯形河床的运河。坡度变大（从0.005增加到0.007）的渠化河段可以高效地接收邻近农田中排出的积水，更快地将洪水引至下游，使得下游洪峰流量增加。20世纪60年代，由于需要在艾尔河的河道位置建设工业建筑和主要公路，位于艾尔河最下游1.5km长的河段被迫从涵洞流过^[23]。一旦超过涵洞允许通过的最大流量（65m³/s），河水便会溢出并淹没部分工业区。1987年，一条洪水旁通隧道建成，直接将部分水量以50m³/s的流速分流到了罗纳河，降低了艾尔河下游的洪灾风险。

erode, deposit, or migrate if there is a high degree of urban encroachment up to the banks. In such cases, natural elements can be incorporated into restoration schemes, but the channel must typically be hardened to resist erosion and undermining of infrastructure (upper left corner of Figure 1). In highly urban settings, “restoration” of straightened or canalized channels can be likened to “gardening,” where desired elements can be incorporated into the projects, but they are not sustained by current fluvial process, and thus require maintenance (lower left corner of Figure 1)^[6]. In such highly urban settings, social benefits may outweigh ecological.

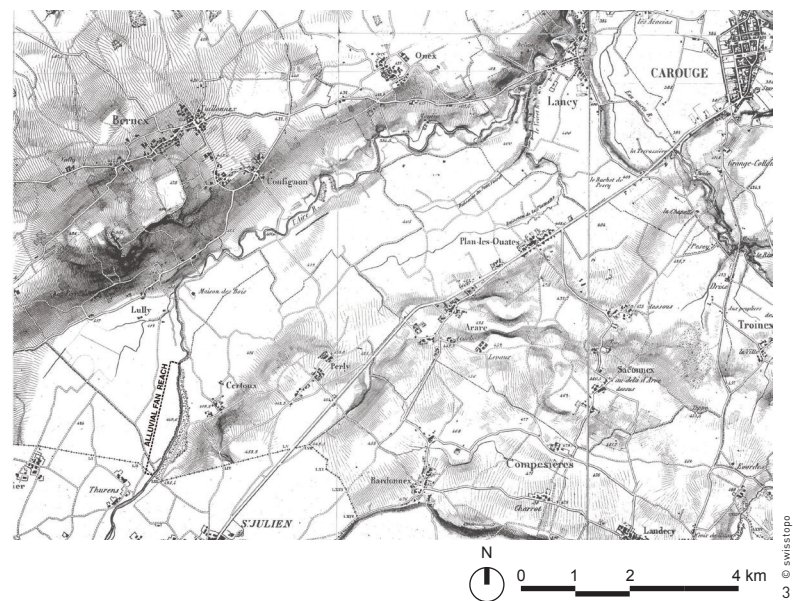
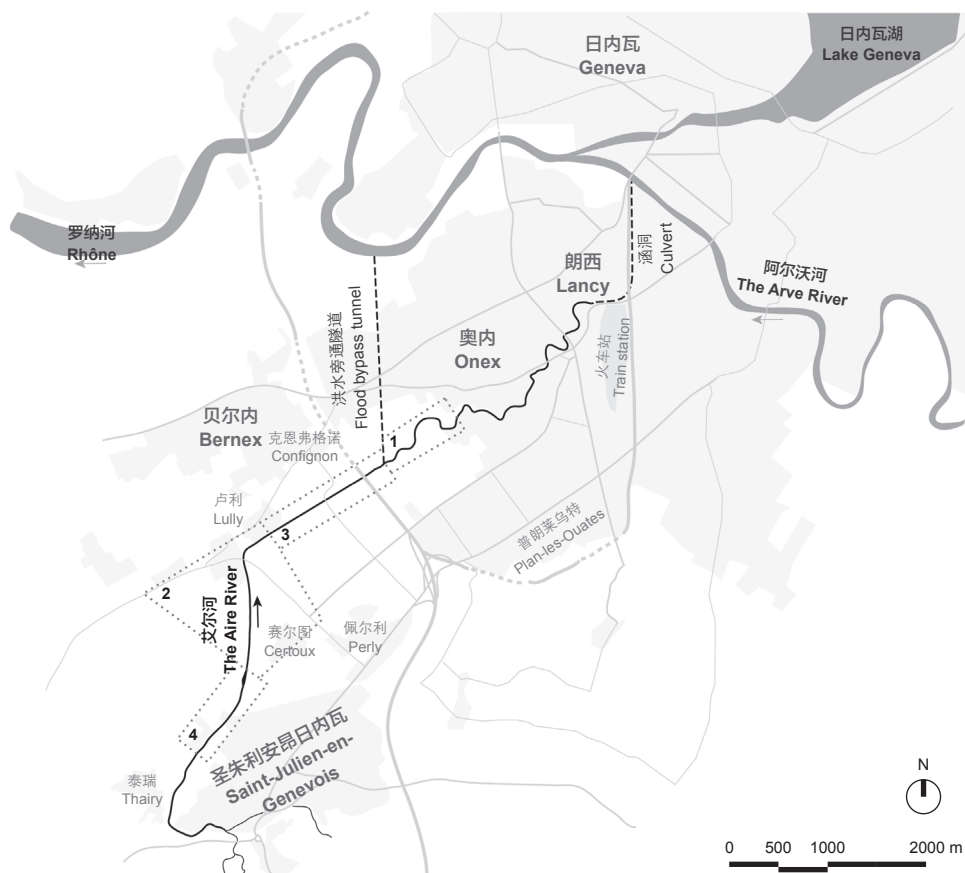
The Aire and Isar Rivers illustrate the limitations and also the possibilities of urban rivers provided the process space is increased to create a limited *espace de liberté*. Both are large projects completed within the last decade (the final stage of the Aire is still ongoing) and within large urban areas: the Aire being peri-urban, in an area zoned deliberately for preserving agricultural use entirely surrounded by urbanization now, as a “Central Park” in Geneva; the Isar flowing through the city center of Munich. Both rivers drain the Alps and have sufficient stream energy to rework their channels. In the case of the Isar this is thanks to flow releases to rejuvenate geomorphic processes.

5 The Aire, Geneva: A Peri-urban River

The Aire River project restored ecological function to a formerly canalized river by providing the river with an *espace de liberté*, within which the river is free to flood its banks, erode its bed and banks, and deposit bars. Through these processes, the river has created complex aquatic habitats and riparian corridor, which in turn can support the complex food web of the riverine ecosystem.

5.1 Setting

The Aire drains a 100 km² catchment, flowing northward from the Salève range of the French Alps, through glacial moraines, onto the Plaine de L’Aire in southwestern Geneva, a broad basin through which the Aire is naturally unconfined and alluvial (Fig. 2)^[15]. Prior to engineering modifications, the Aire had a braided channel across its alluvial fan, then transitioned to a single thread meandering channel (sinuosity 1.46) and flowed eastward to its confluence with the Arve (Fig. 3). To improve drainage and more efficiently convey floodwaters, 3 km of the meandering channel were artificially straightened and converted to a trapezoid with concrete banks and bed in the late 19th and early 20th centuries. This “Channelized Reach” had a higher gradient (increased from 0.005 to 0.007), efficiently draining adjacent agricultural lands and routing floodwaters downstream more quickly, increasing peak flood discharge delivered downstream. In the 1960s, the downstream-most 1.5 km of the Aire was put in an underground culvert to permit building of industries and a major highway over its former course^[23]. However, if the culvert’s 65 m³/s flow capacity is exceeded, parts of the industrial area will be flooded. In 1987, a flood bypass tunnel was completed to divert 50 m³/s directly to the Rhône, reducing flood hazard to the lower Aire.



2. 日内瓦州艾尔河的区位图：河段被标记为4段，分别对应项目的4个实施阶段（来源：参考文献[13]）。
3. 从1871年的“杜福尔地图（瑞士地图集）”中可以看出，艾尔河在冲积扇上所呈现出的宽阔曲折的河流形态。
2. Location map of the Aire River, Canton of Geneva. Reaches marked as 4 phases in the project [Source: Ref. [13]].
3. The Aire River as depicted on the Carte Dufour of 1871, showing wide dynamic major bed on the alluvial fan reach.

虽然渠化可在洪水来临时，提高河段自身输水效率，但它转移甚至加剧了下游的洪水风险。随着气候变化的持续发生，预计在未来的几十年中，还将出现更强的降水和随之而来的更严重的洪水。因此，有必要提升艾尔河上游高人口密度的城市区域内河段的蓄洪能力。

5.2 艾尔河修复

1997年，日内瓦州修订了《水法》，旨在改善艾尔河的河流水质、提高其生态价值与可达性，并设立了专项基金用于修复此河流^[25]。基于水文学、景观学、生态学和河流管理学的研究^[24]，日内瓦州采取了“半保留，半修复”的策略——保留部分硬化渠道以供周边大量居民活动，同时营建出一条南北向连通农业用地的滨河廊道，为河流恢复复杂形态提供充足空间^{[15][25]}。此外，为进一步减少下游的洪灾风险，建设两道横穿河漫滩的护堤兼阻水设施以蓄积洪水。

艾尔河的修复工作从2002年开始，分为四期进行（图2）。本文重点介绍第三期河段运用的修复方法与其最终效果。在这期河段的修复工

While the channelized reach increased effectiveness of flood conveyance, it displaced (and exacerbated) the flood problem downstream. As climate changes, more intense precipitation and thus more intense floods are anticipated in coming decades. Thus, there was a motivation to create a greater flood storage for the Aire upstream of the dense urban reach.

5.2 Restoring the Aire

The Canton of Geneva revised its water law in 1997 to require improved water quality, enhanced ecological values, and better public access to the Aire, and established a fund to support the revitalization of the river^[25]. After completing studies of Hydrology, Landscape, Ecology, and River Management to provide a basis for restoration strategies^[24], the Canton selected a restoration approach that retains portions of the straight canal to provide public access for the large urban population nearby, while creating a corridor to the south from agricultural lands, where the river can rebuild a complex morphology^{[15][25]}. In addition, the project included two berms cutting transversely across the floodplain, along with flow control structures, to impound floodwaters, thereby reducing floods downstream.

Restoration of the Aire has been underway in four phases since 2002 (Fig. 2). This paper focuses on the restoration approach in the Phase 3 reach. Here the restoration project repurposed components of the old canal as recreational sites,



4. 左图拍摄于2014年4月，展现了菱形沟渠刚刚开挖完成时的状态；右图拍摄于一年后，此时的河床已在较低强度（但有效）的水流冲刷下发生了改变。

4. The left is the photo of freshly cut channels (and lozenges) in April, 2014; the right is the Aire channel one year later (April, 2015), after modest (but still geomorphically effective) flows re-arranged the bed.

作中，原运河的一部分被改建为休闲场所，同时在毗邻运河的一侧农田中开挖了一条平行河道，其地形被塑造为菱形网络，以允许水流冲刷、侵蚀，并最终演变为复杂的河道形态（图4）。虽然河水可以在平整的坡面上侵蚀出自己的河道，但菱形沟渠可以加速其演变过程，并通过带有视觉冲击力的外观彰显设计理念——让河流自己规划路线——这是一个经过深思熟虑后的设计方案^[26]。

从航拍图上可以看出艾尔河的自由流动是如何改变菱形几何图案的（图5）。如今，经历了多场小型洪水冲刷的艾尔河已然演变为一形态复杂、生境多样的河流（图6）。

5.3 过程修复效果评估

5.3.1 空间

艾尔河修复项目拓宽了河流自由流动的空间，将河道宽度从原本的15m向南拓宽为100m。此外，当遭遇大型洪水时，这片横向的菱形沟渠可有效减缓洪水的冲击和破坏力，并起到蓄积洪水的作用，减少了下游人口稠密地区的洪水风险。

5.3.2 能源

虽然项目在挖掘沟渠时也会使用重型设备，但通过预留菱形岛屿（而非按照设想挖出一条完整的河道）可以最大程度地减少挖掘和搬运土方所需的化石能源。最重要的是，洪水的动能可用于塑造河道。即使是一系列重现期小于2年的洪水，也足以侵蚀菱形岛屿，并淤积成砾石滩等自然河流形态的组成要素，河岸植物群落也在这一过程中逐步形

while creating an adjacent, parallel freedom space (from former farmland). The diamond-shaped bits of land left between these channels (“lozenges”) gradually erode and evolve as the river migrates, creating complex channel forms (Fig. 4). While the river could have eroded a channel into a graded flat surface, the grid of channels serves to accelerate the evolution of the channel, and provides a striking visual pattern for the public, conveying the idea that allowing the river to select and develop its own channel is a deliberate choice and not an oversight^[26].

Viewed from above, it can be seen how the Aire has chosen a course through the lozenge template (Fig. 5). With a series of relatively small floods, the Aire has evolved into a complex channel with diverse habitats, both aquatic and riparian (Fig. 6).

5.3 Process-Based Restoration Evaluation

5.3.1 Space

The Aire River restoration increased process space of the river, increasing the channel width from the 15 m to 100 m created to the south. Moreover, the transverse dikes that impound floodwaters across the floodplain during large floods, effectively increase the river’s footprint across its floodplain as they reduce the magnitude of large floods in densely urbanized downstream reaches.

5.3.2 Energy

Heavy equipment was used to excavate the multiple channels, but by leaving the lozenge-shaped islands 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 lozenge-shaped islands and deposition of natural fluvial forms such as gravel bars. With the establishment of riparian vegetation over the past 7 years, the evolving channel



July, 2014



August, 2014



October, 2014



November, 2014



April, 2015



May, 2015



August, 2015



October, 2015



May, 2016



© Fabio Chironi: Superpositions Group, Atelier Descombes Rampini SA

成。经过7年中河流冲击与植被固土的相互作用，不断演变的河道已逐渐呈现出清晰的形态。

5.3.3 材料

除了几个关键节点（如设置道路等基础设施所在的场地）外，艾尔河的河岸没有使用任何外源石块或其他材料进行硬化。相反，为了恢复

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.

5.3.3 Materials

Except for a few key sites (e.g., at infrastructure crossings), the banks were not hardened with boulders or other elements imported from elsewhere. Rather,



© Georges Descombes

5. 从2014年7月到2016年5月的第三期河段航拍图，展示了自菱形沟渠开挖完成后的3年中，河道在中等强度（低于2年重现期）的水流冲刷下逐步形成的形态。
6. 拍摄于2021年9月的第三期河段，此时，艾尔河河道已经历了7年多的冲刷。可以看到，在泥沙输移和淤积的双重作用下，菱形沟渠中已形成了复杂的河流形态，并建立了滨水植物群落。
5. Air photos (mosaic from drone imagery) of the Phase 3 reach as it evolved from July, 2014 (when the criss-crossed channels were freshly cut) to May, 2016, show the rapid evolution of the river bed under the influence of moderately high flows (none exceeding 2 years in return period).
6. The Aire River within the Phase 3 restoration reach over 7 years after the river began flowing through the lozenges (photo taken in September, 2021). Complex riverine forms developed from the interaction of sediment transportation and sedimentation of flow in the lozenges, establishing riparian vegetation.

河流的自然形态并促进河岸植被生长，设计方案有意引导侵蚀和淤积作用的发生。场地中从冰川时期遗留下的自然沉积物颗粒成分多样、大小不一，如致密的黏土、大块砾石和鹅卵石等。单个菱形岛屿的演变会在较大程度上依赖其成分，如由黏土构成的菱形岛屿就比砾石构成的更耐侵蚀。

5.3.4 时间

该项目并未“修建”河道，只是为其“搭建场地”，让河流自己设计形态，这一过程显然需要时间。此设计方案的创新始于由菱形岛屿分隔而成的纵横交错的沟渠网络，它有趣的外观为这片城市开放空间赋予了独特的视觉属性，公众可在此直接观察到河流与河道的演变过程——时间已经展现出可喜的变化，河流将会逐渐完成自我塑造。

5.3.5 局限性

如上所述，这种过程修复的方法并不适合所有场地，因此有学者对整条艾尔河是否都适用这一方法提出了质疑^[15]。幸运的是，此场地中可沿着南部的农业用地修复一些曾经的河流廊道，以提供给艾尔河更大的流动空间，并通过修建洪水旁通隧道降低了艾尔河下游长约1.5km的河段（与阿尔沃河交汇处）的洪峰流量。然而，由于这段自发形成的河道目前已有两处拓展至预留空间的南部边界，这意味着此河段可能需要超过100m的宽度。迄今为止，这一项目成效显著，因此，项目团队正在考虑进一步向南扩建河流廊道，但这一举措将占用更多农业价值较高的用地，这也成为需要解决的挑战。

此外，根据对于四期河段在冲积扇上挖掘形成的沉积盆地中和二期河段在为深水鱼类提供栖息地而建造的水池中的泥沙沉积速率的观测，可以发现，艾尔河仍在发生充分的水流冲刷，并随水流在河道底部留下了充足泥沙，改变了地貌并建造出复杂的河道形态。综上所述，艾尔河拥有足够的水流动力和输沙量来重建河道。^[15]

与许多传统的北美修复项目不同，艾尔河的修复方案并未建造一个稳定的理想化河道形态，而是为河流自由的动态演变预留空间；同时并未在允许河流可能流经的区域设置灰色基础设施，而是尽可能地减小限制河流横向摆动的阻碍。

the banks were encouraged to erode and deposit in response to the river's flow pattern 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 lozenge-shaped islands was influenced in large measure by their composition, with the islands cut in clay being more resistant to erosion than those composed of gravel.

5.3.4 Time

The project did not “construct” the river channel, but simply “set the stage” for the river to form its own channel, a process that requires time. The innovative starting condition of the excavated network of criss-crossed channels separated by lozenge-shaped islands resulted in a visually interesting pattern being developed from the outset, which was an important attribute in this very visible urban setting. Time was critical in the process, as the public could observe the evolution of the river and its channels over time. The narrative around the project made clear that change was anticipated and welcomed, that the river would be the author of its own geometry over time.

5.3.5 Limitations

As discussed above, such process restoration may not be feasible everywhere, and questions were raised about whether the Aire was well-suited to the approach^[15]. Fortunately, 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 and reducing the peak flow conveyed downstream to the lowermost 1.5 km of the Aire (before its confluence into the Arve), where a flood bypass tunnel with limited capacity had been built. 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 the success of the project to date, an expansion of the river corridor to the south is now under consideration, but converting more agricultural land back to river corridor is tricky because of the high value of the agriculture.

Moreover, it was clear that the Aire still experienced frequent geomorphically-competent flows, and that it had sufficient sediment load to build complex channel forms, based on observed rates of sediment deposition in a sediment basin excavated on the alluvial fan (Reach 4) and in a pool excavated to provide deep-water fish habitat (Reach 2). Thus, the Aire has sufficient stream power and sediment load to recreate its channel.^[15]

Unlike many conventional restoration projects in North America, which seek to create a stable idealized form, even in settings where the channel could have migrated freely with infrastructure conflicts, the restoration concept for the Aire identified the zone within which the river could be free and removed constraints on its lateral mobility.

6 慕尼黑伊萨尔河：一条城市河流

伊萨尔河的修复策略为利用粗泥沙创造可侵蚀河床和堤岸，预留出河流发生动态演变、侵蚀和淤积作用的空间，并重塑8km长的可达河岸线。2011年，自修复计划（即“伊萨尔河计划”）完工以来，人工加沙和拓宽河道等措施促进了泥沙输移作用，并最终形成了砾石滩——其形态因洪水影响而持续演变，创造出具有更多物种的栖息地（图7）。

6.1 背景

作为多瑙河的主要支流之一，伊萨尔河源自奥地利阿尔卑斯山，穿过多处冰碛后流经慕尼黑的砾石平原，最终向北流入巴伐利亚州^[27]。慕尼黑最初将城池建设在伊萨尔河西侧河畔，借助一个河心岛修建了一座桥^[28]，这座桥也是罗马时期慕尼黑得以连接伊萨尔河两岸的唯一通道，并为慕尼黑城市向东岸的扩张提供了机会。最终，慕尼黑以伊萨尔河为中心轴向外扩张，发展成为一个富足的贸易之城。^[29]

19世纪初期，水务机构开始了长达一个世纪的伊萨尔河开发计划，1950年左右，河道已转变为一条狭窄的混凝土通道。20世纪初开始，鉴于伊萨尔河流量充沛和落差巨大的有利条件，人们决定大力建设水电站。在后来不到百年的时间内，伊萨尔河上共建起了30座水电站，这极大地改变了河道的水文情况。

水电站的建造对生态造成的影响包括洄游鱼类如多瑙哲罗鱼（*Hucho hucho*）的数量减少，以及先锋植被如具鳞水柏枝 [*Myricaria germanica* (L.) Desv.] 的面积减少。^[30]因此，自20世纪30年代起，就有民间团体开始反对建设水电站^[31]，尤其当水电站建设引发了河流改道甚至完全干涸的情况时，如1959年建成的希爾文斯坦水库^[32]在发挥洪水防控和水力发电功能的同时，只能为伊萨尔河下游提供恒定的基础流量^[33]。直到1984年，《巴伐利亚宪法》第141条将环境保护明确设立为州级层面的目标^[32]；1987年，《巴伐利亚水务法》制定法规要求保证河流的最低基流值；同年，由慕尼黑市环保局、水务局、规划建设部门、伊萨尔安联集团等非政府组织，以及众多的规划、生态和水文学专家组成的跨学科合作团队在慕尼黑组织召开会议，共同商议伊萨尔河慕尼黑河段的修复计划^[31]。

6.2 伊萨尔河修复

合作团队发现慕尼黑易受洪水侵袭，并且预计降水量将会因气候变化影响增长25%，洪峰流量也将相应提升12%^{[34][35]}；此外，他们还意识

6 The Isar, Munich: An Urban River

The Isar River exemplifies restoration of coarse sediment load, creation of erodible bed and banks in place of formerly rigid boundaries, expanded process space for river migration, erosion, and deposition, and increased human access to the river over 8 km. Since the implementation of the restoration program (called the 'Isar-Plan,' completed in 2011), the natural transport of sediment made possible by artificially adding sediment and enlarging the river's process space has resulted in deposition of gravel bars, whose forms sequentially adjust and evolve during floods, providing increased diversity of habitat and species that depend upon the habitats (Fig. 7).

6.1 Setting

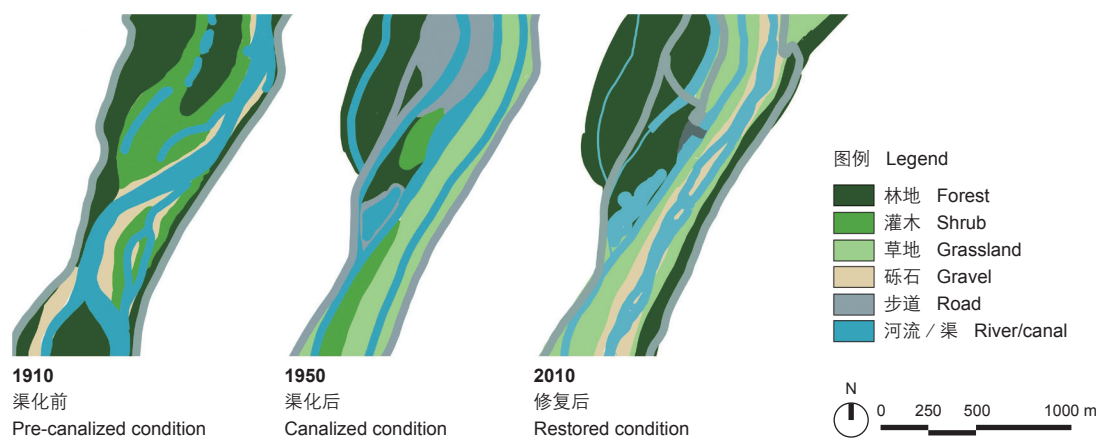
As one of the principal tributaries of the Danube, the Isar River drains the Austrian Alps, flowing northward into Bavaria. Leaving the high mountains, it traverses multiple glacial moraines and flows across the gravel plain of Munich^[27]. Munich was first settled on the west bank of the Isar at the location of a bridge built to take advantage of an island that allowed the river to be crossed in two shorter sections^[28]. During the Roman period, this bridge was the only crossing of the Isar, and Munich developed as a rich trading city, which expanded to the east bank^[29].

After floods in the early 19th century, the water agencies started a century-long process of regulation of the Isar, forcing the river into a narrow concrete channel by 1950. The Isar's generous flow and steep gradient stimulated a boom in construction of hydroelectric dams starting in the early 20th century. In less than 100 years, 30 hydropower plants were built, resulting in large changes to the hydrograph.

The ecological consequences included decreased populations of migratory fish such as the Danube Salmon (*Hucho hucho*) and reduced area of pioneer vegetation, e.g., *Myricaria germanica* (L.) Desv.^[30] There was opposition from civil society to the construction of hydropower plants starting in the 1930s^[31], especially as the river was completely dried up downstream of the diversions for hydropower plants. Sylvenstein Reservoir (1959)^[32] was built to provide a constant minimum base flow to the river downstream, in addition to flood control and hydropower generation^[33]. In 1984, Article 141 of the Bavarian constitution made environmental protection a goal of the state^[32], and in 1987, the Bavarian Water Law called for minimum base flow in rivers. That year, a working group from Munich's environmental agency, water agency, planning and building departments, NGOs including the Isar Allianz, and experts from planning, ecological and hydrological sciences began meeting to plan the restoration of the Isar in Munich^[31].

6.2 Restoring the Isar River

The working group recognized that not only was Munich vulnerable to floods, especially with a predicted 25% increase in precipitation and an expected 12%



7. 伊萨尔河上2 km长的修复河段（修复河段总长8 km）在1910–2020年间的河道演变细节图。值得注意的是，1910年还随处可见的砾石滩在1950年时已全然消失，但在2010年又重新显现。

7. The 2-km within the 8-km restored reach of the Isar River from 1910 to 2010. Note that open gravel bars were abundant in 1910, entirely absent in 1950, but reappeared in the restored channel in 2010.

到伊萨尔河可以为不断扩张的城市提供开放空间和市民休闲场所^[36]。最终，该会议确立了三个同等重要的目标：1）降低洪水风险；2）进行生态修复；3）提升休憩功能^[37]。

为降低洪水风险，他们制订了三个措施：拓宽河道、增加特定区域内的河道与河漫滩的过洪能力、退让并抬高部分防洪堤。生态修复与休憩功能提升方面的措施则包括：1）设定流经城市的最低基流值的基础上允许河流发生更自然的流量变化，拆除混凝土堤岸使河流侵蚀作用得以发生，同时机械式添加砾石作为原材料来重塑砾石滩和河流形态、丰富河床内水流的速度变化，最终塑造出更为自然的河流形态；2）顺应地势坡度建设多层不规则石阶（也称为“蜂窝”结构）取代拦截河道的笔直的混凝土堤堰，以恢复鱼类的洄游路径和人类休闲漂流活动——通过在更长的河段内形成落差相同的石阶，为鱼类洄游提供足够的通道。这两项措施不仅恢复了河流纵向与横向的连续性，也重建了动植物生境。此外，砾石滩的建造主要是为与拓宽的河流廊道相互结合，以增加河道内的泥沙淤积，同时将其打造为大型的石滩休憩场所（模拟伊萨尔河源头的阿尔卑斯山的景致），可供人类和野生动物共同使用（图8）——如多瑙哲罗鱼这样以砾石滩为栖息地的物种，人们发现它们已经开始在修复后的河道和河漫滩的砾石河床上产卵。除此之外，伊萨尔河沿岸也在进行着许多其他修复项目，有助于加速河流侵蚀和泥沙输移作用。

重获生机的伊萨尔河仿若阿尔卑斯山脚下的迷人河景，尤其是新增的砾石滩，已然成为了人们放松、亲水和烧烤的热门场所，河流整体的休闲功能得到了提升。此外，上游实施的污水处理措施改善了水质，这既满足了市民游泳休闲的需求又有助于生态系统恢复（图9）。

increase in flood peaks due to climate change^{[34][35]}, but also the Isar had the potential as an open-space and recreational resource for the growing city^[36]. In response, they identified three equally weighted goals: flood risk reduction, ecological restoration, and recreation improvement^[37].

Flood risk reduction was achieved by widening the river, increasing the flood conveyance capacity of the channel and the floodplain within the designated river corridor, and setting back and raising some flood control dikes. The measures of ecological restoration and recreation improvement included a more natural flow regime (with a minimum base flow through the city), and removing concrete embankments and allowing natural bank erosion. Mechanical additions of gravel provided the raw materials with which river flows could deposit gravel bars and complex river forms, thereby increasing velocity variation within the riverbed. Straight concrete weirs, extending across the channel as barriers to fish migration and recreational rafting, were removed and replaced with multiple, irregular rock steps (also termed “honeycomb” structures) that accommodated the same elevation drop but over a longer channel length, which provided pathways for fish migration. These measures helped restore longitudinal and lateral continuity, recreating natural habitats for animals and plants. Gravel bars were built up in response both to the wider river corridor (and thus greater depositional opportunities across the channel), and to the increased gravel supply, forming large gravel bars (corresponding to the alpine sources of the river) that serve wildlife and human recreation (Fig. 8), including gravel-dependent species such as the *Hucho hucho* which was found to spawn on gravel beds of the restored channel and floodplain. Many restoration projects are being implemented all along the Isar to enable active erosion and sediment transport.

Recreation was enhanced as the once-again dynamic river became an attractive and near-natural alpine riverscape, with new gravel bars providing places to relax and access the water, grilling areas provided in recreational hotspots, and upgraded sewage treatment upstream to improve water quality for both swimming and ecosystems (Fig. 9).

该项目以“伊萨尔河的新生活”为口号，于2000年动工，2011年完工^[38]。修复计划恢复了部分水流量和输沙量，并移除了影响河流形态自然演变的障碍物。通过水流侵蚀和泥沙淤积作用帮助构建了自然化的河流景观。8km长的河段从南（上游）到北（下游）被分成三期依次进行修复，每期修复工程之间会留出时间来让河流适应修复后增加的水流动力和输沙量^[37]。2005年，伊萨尔河经历了一场百年一遇的大洪水，极大地改变了河床形态，并将部分河漫滩相互连接，但河流整体仍未超出预设的河流廊道范围，并未对城市构成威胁。如今，鱼类物种数量正在恢复，修复后的河岸也为公众提供了大量开放空间。

6.3 过程修复效果评估

6.3.1 空间

为了降低洪水风险而退让的两侧河堤增加了河道输水量，并恢复为具有自然基底的缓坡堤岸。修复前，伊萨尔河河漫滩的防洪堤结构只能容纳 $800\text{m}^3/\text{s}$ 的洪水流量（而百年一遇的洪水流量为 $1\,150\text{m}^3/\text{s}$ ^[39]），修复后则可达 $1\,200\text{m}^3/\text{s}$ 。

此外，尽管河道由原本的50m整体拓宽至90m，但是在地势较低的弗劳赫河漫滩，考虑到河床可能会发生强度更大的动态演变过程，河道将被进一步拓宽，这为河流预留了可以肆意侵蚀、淤积和演变的空间。

6.3.2 能源

在建造过程中，使用推土机、挖掘机和其他重型设备打破防洪堤，使堤岸线后退并设置特定设施来促进河流修复。此外，在拆除岩石墙和混凝土堤岸后，建设了允许河流自然侵蚀的砾石滩，这将进一步缓和并

Under the title, “New Life for the River Isar,” the project was implemented from 2000 to 2011^[38]. The restoration partially restored flow and sediment load, as well as removed constraints on natural fluvial processes. These fluvial processes were then permitted to create natural fluvial forms through erosion and deposition. The 8-kilometer long reach was restored from south (upstream) to north (downstream) in three sections, paused in between to let the river adjust to the removal of constraints and increased flow dynamics and sediment load^[37]. In 2005 the Isar experienced a large (100-year) flood, which greatly re-shaped the riverbed and connected parts of the floodplain, and which was contained within the designated corridor, i.e. it did not flood the city. Fish species are recovering, and there is strong public use of the restored river.

6.3 Process-Based Restoration Evaluation

6.3.1 Space

To achieve the flood risk reduction goal, levees were set back to increase conveyance capacity and restore gently-sloping banks with natural substrate. Prior to restoration, the Isar floodplain with the levee system was able to convey only $800\text{m}^3/\text{s}$, whereas the estimated 100-year flood was $1,150\text{m}^3/\text{s}$ ^[39]. The restoration increased the channel flow capacity up to $1,200\text{m}^3/\text{s}$.

Furthermore, the overall width of the river was increased from about 50 m to 90 m, and in reaches with a low floodplain such as the Flaucher, the width over which active river processes can occur was increased further, providing an *espace de liberté* where the river could “play” (erosion, deposition, and shifting of channels).

6.3.2 Energy

Bulldozers, excavators, and other heavy equipments were used during the building process, mostly to remove infrastructure constraints, but also to set-back levees and install features designed to prompt river recovery. Rock walls



8. 修复后的伊萨尔河更为宽阔且颇具野趣，并在河道中央形成了砾石滩（拍摄于2012年7月）。
9. 修复后，处于繁华城市中心地区的河间砾石滩（拍摄于2012年7月）。
8. Mid-channel gravel bar in broader, wilder reach of the restored Isar River (photo taken in July, 2012).
9. Mid-channel gravel bar in dense city-center reach of the restored Isar River (photo July, 2012).

塑造不规则的河岸边缘，同时也为河流的淤积作用提供原料。2005年的大洪水期间（项目进行期间）发生了许多肉眼可见的变化，已拆除防洪堤的河段借助此次洪水的冲击力改变了其河道和河漫滩形态。

6.3.3 材料

此次项目中，景观规划师特别重视对适用于当地地理环境的本土材料的选用^[37]。比如，用于修复自然河岸的砾石来自希尔文斯坦水库；石质座椅的原料取材于当地石材厂；在重型设备施工结束后，用于种植并更新现有草坪的草籽也产自当地；多种野生草本植物群落则移植于慕尼黑北部的草原自然保护区。

6.3.4 时间

伊萨尔河修复工程历时近10年，但这些修复工作仅是为促使河流水文形态和生态功能发生变化而进行必要的人工干预。自从修复计划施工以来，河流的输移作用使泥沙在预留的河道空间内逐渐堆积，形成了砾石滩，而其形态也因洪水的冲击而发生了进一步的调整和演变，栖息地和物种的多样性都有所增加。

6.3.5 局限性

伊萨尔河修复计划的成功实施归因于能源生产商不再享有过去几乎不受限制的水资源使用权。水务局和能源生产商就将伊萨尔河恢复为一条更自然的河流的目标达成一致，但仍未能恢复到最初的状态。此外，从目前的河流廊道来看，伊萨尔河洪水流量的大幅降低也依赖于上游大坝的调节。如果需要完全恢复如初，则需进一步拓宽河床以适应更大的河水流量^[40]。

由于希尔文斯坦水库拦截了河流中所有的天然泥沙和粗质砾石，使得伊萨尔河在流经慕尼黑时泥沙有所不足。为了部分恢复河段泥沙输移作用的连续性，需要将砾石不断地从水库中挖出，并由卡车运送至下游，在那里水流可将其重新冲刷成天然的砾石浅滩^[33]。

与此同时，满足人类使用需求和改善生态环境之间仍然存在矛盾。本项目的成功之处在于试验性地引入了濒危的河漫滩植物——具鳞水柏枝，虽然这种植物在人类活动频繁的地方死亡率很高，部分原因是植物

and concrete embankments stabilizing the banks were removed, and the gravel banks were allowed to erode, softening and making irregular the bank edges and contributing gravel to the river's sediment load. Many of the observed changes occurred during the large flood in 2005, midway through the project, when the reaches whose infrastructure was already removed could take advantage of the flood energy to rework their channel and floodplain.

6.3.3 Materials

Landscape planners paid particular attention to the use of materials that were geo-morphologically appropriate to the site^[37]. For example, the gravel used to restore the natural riverbed was dredged from the Sylvenstein Reservoir; the stones used to create seating matched with locally occurring existing stones; the seeds used to replant the meadows after the transit of heavy equipment and to replace the existing recreational grassland were sourced from local producers; and a mix of wild species naturally existing in protected meadows for nature conservation in the north of Munich was used.

6.3.4 Time

The Isar restoration took around 10 years, but the restoration dealt with only the mechanical changes that were needed to enable a passive hydro-morphological restoration of the form as well as of the ecological function of the river. Since the implementation of the restoration program, natural transport of sediment through the enlarged process space of the river has resulted in deposition of gravel bars, whose forms sequentially adjust and evolve during floods, providing increased diversity of habitat and species.

6.3.5 Limitations

The Isar River restoration was possible because the virtually unrestricted water rights previously enjoyed by the energy producers expired. The water agency and the energy producers agreed on a more naturalized flow regime, but still much lower than the Isar's unregulated flows through Munich. It is important to note that the current river corridor assumes the currently impaired flow regime of the Isar, with greatly reduced flood flows due to regulation by upstream dams. If the full natural flow were to be restored, further broadening of the riverbed would be necessary to accommodate the high flows^[40].

Because Sylvenstein Reservoir traps all of the river's natural sand and gravel load, the Isar was flowing into Munich in sediment deficit. To partially restore the continuity of sediment transport, gravel is dredged from the reservoir and transported by truck to locations downstream from which flows can redistribute it into natural riffle and bar forms, a practice that will need to continue so long as the dam traps the coarse sediment load^[33].

Meanwhile, there were still some conflicts between the improved both human use and ecological condition. Experimental reintroduction of the endangered

幼苗会被孩童从砾石中拔出^[41]。此外，修复工程通过扩大本地区一种特殊的鱼类——鼻鱼 [*Chondrostoma nasus* (L.)] 的种群适合活动的生境范围，改善其栖息地条件。但是由于栖息适宜度最高的区域与人类活动相对频繁的区域相互重叠，种群繁殖行为会受到影响，尤其在夏季，河畔野餐和游泳最为盛行之时，人类活动可能会侵占鼻鱼的生存空间^[42]。

伊萨尔河修复工程的总造价是3 500万欧元（约合2.6亿人民币），相较于8km长的河流所取得的效益而言实在是微不足道，尤其是这条河流位于快速发展的城市中心——修复项目往往受到场地内受保护区域和历史性建筑，以及穿河而过的地铁等地下基础设施的限制^[38]。所以，很大程度上伊萨尔河的实际修复效果应当归功于干预方式。此项目并未借助重型机械去塑造一种最终的河道形式，而是通过拆除周围人造设施来给予河流更多的演变空间。

7 结论

通过预留出自然的河流动态演变过程所需的空間，让其实现自我修复是一种行之有效的河流修复方法，可以提高修复成功率，也能帮助实现项目的成本效益最大化。这一方法需要为河流提供可发生动态演变、自然侵蚀和淤积作用的空間——显然，相较于城市环境，乡野环境更容易实现这样的需求。因此，虽然《欧盟水框架》指令出台以来，欧洲进行了多个河流修复项目^[14]，但位于城市区域的案例并不常见。而艾尔河和伊萨尔河的修复则证明了过程修复方法在城市区域的适用性——即使是在城市化地区，也有可能找到适合修复的土地（比如农田、停车场和废弃工业地块）以及可拆除的固化驳岸。

此外，这两个项目都满足了过程修复方法的4个指标：空间、能源、材料和时间。它们共同展示了通过修复河流动态演变过程来修复城市河流，并实现生态和社会效益的可能性。首先，满足改进洪水风险管理的需要——艾尔河通过建造河堤和水流控制结构将洪水储存至农田低地内，减少了下游的洪峰流量；伊萨尔河通过拓宽河道和退让河堤的方法，留出河流动态演变的空间，可以容纳更多洪水径流，进而降低了洪

floodplain plant *Myricaria germanica* (L.) Desv. showed success overall, but high mortality rate in areas of intense human use, with loss of plants due in part to young plants being pulled from the gravel bars by toddlers^[41]. The restoration improved habitat conditions for a target native fish species, the common nase [*Chondrostoma nasus* (L.)], with greatly expanded areas of suitable physical habitats for population conservation but low suitability for recruitment. Moreover, the areas of most suitable habitat for the nase coincided with the areas of more intense human use, implying that at least during the summer season when riverside picnicking and swimming are most popular, human uses may drive out the nase^[42].

The total cost of the Isar River restoration was €35 Million, relatively modest for the benefits achieved over an 8-km length of river, especially in an urban area with multiple constraints—including the existence of protected areas and buildings within the project area, and underground infrastructures such as subways crossing under the river^[38]. This is attributable in large measure to the types of interventions, which did not involve shaping of final channel forms with heavy equipment but rather removing infrastructural constraints and giving the river more room in which to move.

7 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. Process restoration and the *espace de liberté* approach require room for the river to be dynamic, eroding and depositing, and this is more likely in rural settings than urban ones. While there are now many examples of such projects in Europe since adoption of the Water Framework Directive^[14], they have been less common in urban areas. Both the Aire and Isar demonstrate that the process restoration approach can have applicability within urban areas—even in an urbanized region, it is often possible to find lands adjacent to the river channel that are suited for restoration to a river corridor (such as agricultural, parking lots, and abandoned industrial parcels) and opportunities to remove hardened bank protection structures to expand the width of the river's process space.

The Isar and Aire Rivers provide compelling examples of process-based restoration as viewed in the framework of four criteria: space, energy, materials, and time. The two projects demonstrate the possibilities of urban river restoration to achieve both ecological and social benefits through restoration of fluvial process. First, both projects were motivated in part by the need to improve flood risk management. On the Aire, berms and flow control structures were built to store floodwaters on agricultural valley bottomland, to reduce the peak flow conveyed downstream. On the Isar the active channel was widened and flood control berms were raised to increase the flood conveyance, thereby reducing the likelihood of overflows into the adjacent urban areas. Second,

水蔓延至临近城区的可能性。其次，在促进生态系统恢复的同时提高了公众可达性、增加了居民休闲机会。

以艾尔河和伊萨尔河为代表的大部分欧洲河流修复项目所采用的模式与北美地区的模式（即借助巨石和其他大型设施来稳固河岸的蜿蜒河道）形成了鲜明对比。北美地区人们对“整治”河道的需求从侧面反映了人们对河流地貌和水生态的误解（例如，认为硬质河道和稳定的生态系统是有必要的），以及对此类河道的文化偏好^[9]。欧洲的大多数河流修复实践则建立于生态系统和自然作用的新兴理念之上。

随着人们对河流生态系统运作规律的进一步了解，人们已逐渐意识到河流侵蚀、泥沙淤积与河道迁移等自然过程将十分有利于创造高质量栖息地。因此，河流修复的最有效办法往往就是为它留出空间，使其自愈。**LAF**

致谢

作者感谢日内瓦州国土部水务局的亚历山大·维萨德对艾尔河修复项目分析所给予的贡献与支持；感谢来自捷克ADR建筑事务所日内瓦分部Superpositions团队的法比奥·凯龙和格雷戈·布辛拍摄并制作的2014~2016年之间的河道航拍图；感谢巴伐利亚州环境署的沃尔特·宾德为伊萨尔河修复提供的宝贵见解，以及他在促进伊萨尔河生态修复方面所发挥的重要作用；感谢欧盟“地平线2020”研究与创新计划基金项目“以自然为依据”对动物园艺协会针对伊萨尔河修复的支持（项目编号：776681）。

ecosystem restoration and increased human access with recreational opportunities were developed together.

River restoration practice in Europe such as the Aire and Isar projects provide a refreshing contrast to the dominant paradigm in North American river restoration of constructing stable meandering 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 became popular in North America (e.g., notions that stable channels and stable ecosystems were desirable), as well as cultural preferences for such channels^[9]. By contrast, river restoration practice in Europe was able to build on more up-to-date concepts of ecosystems and disturbance.

As we better understand 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. **LAF**

ACKNOWLEDGEMENTS

Analyses upon which the Aire River restoration was based were supported by the Canton of Geneva, and the authors acknowledge the insights and support of Alexandre Wisard of the Office cantonal de l'eau, Département du Territoire, Etat de Genève. Greg Bussien of the Superpositions team (Atelier Descombes Rampini SA) created the mosaic of channel evolution from drone imagery collected by Fabio Chironi of the team since 2014. The authors gratefully acknowledge the insights on the Isar River restoration provided by Walter Binder of the Bavarian Environment Agency and Binder's important role in promoting the ecological restoration of the Isar. The research of AZH on the Isar Rive restoration was supported by the PHUSICOS project, H2020 Grant Agreement (No. 776681).

REFERENCES

- [1] Naiman, R. J., Décamps, H., & McClain, M. E. (2005). Riparia: Ecology, Conservation, and Management of Streamside Communities. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 17(6), 657. <https://doi.org/10.1002/ajq.777>
- [2] Florsheim, J. L., Mount, J. F., & Chin, A. (2008). Bank erosion as a desirable attribute of rivers. *Bioscience*, 58(6), 519-529. doi:10.1641/B580608
- [3] Gurnell, A. M., Piégay, H., Swanson, F. J., & Gregory, S. V. (2002). Large wood and fluvial processes. *Freshwater Biology*, 47(4), 601-619. <https://doi.org/10.1046/j.1365-2427.2002.00916.x>
- [4] Stanford, J. A., Lorang, M. S., & Hauer, F. R. (2005). The shifting habitat mosaic of river ecosystems. *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen*, 29(1), 123-136. <https://doi.org/10.1080/03680770.2005.11901979>
- [5] Naiman, R. J., Decamps, H., & Pollock, M. (1993). The role of riparian corridors in maintaining regional biodiversity. *Ecological Applications*, 3(2), 209-212. doi:10.2307/1941822.
- [6] Kondolf, G. M. (2011). Setting goals in river restoration: When and where can the river "heal itself"? In A. Simon, S. J. Bennett, & J. M. Castro (Eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools* (pp. 29-43). Washington, DC: American Geophysical Union.
- [7] Habersack, H., & Piégay, H. (2008). River restoration in the Alps and their surroundings: Past experience and future challenges. In H. Habersack, H. Piégay, & M. Rinaldi (Eds.), *Gravel-Bed Rivers VI: From Process Understanding to River Restoration* (pp. 703-735). Amsterdam, Netherlands: Elsevier B.V.
- [8] May, R. (2006). "Connectivity" in urban rivers: Conflict and convergence between ecology and design. *Technology in Society*, 28(4), 477-488. <http://dx.doi.org/10.1016/j.techsoc.2006.09.004>
- [9] Kondolf, G. M. (2006). River restoration and meanders. *Ecology and Society*, 11(2), 42. doi:10.5751/ES-01795-110242
- [10] Lave, R., Robertson, M. M., & Doyle, M. W. (2008). Why you should pay attention to stream mitigation banking. *Ecological Restoration*, 26(4), 287-289. doi:10.3368/er.26.4.287
- [11] Doyle, M. W., Singh, J., Lave, R., & Robertson, M. M. (2015). The morphology of streams restored for market and nonmarket purposes: Insights from a mixed natural-social science approach. *Water Resources Research*, 51(7), 5603-5622. <https://doi.org/10.1002/2015WR017030>
- [12] Lave, R., & Doyle, M. W. (2021). *Streams of Revenue: The Restoration Economy and the Ecosystems It Creates*. Cambridge, England: The MIT Press.
- [13] Perini, K. (2016). Emscher River, Germany—Strategies and Techniques. In K. Perini, & P. Sabbion (Eds.), *Urban Sustainability and River Restoration: Green and Blue Infrastructure* (pp. 151-159). Devon, England: John Wiley & Sons.
- [14] European Commission. (2000). *Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy*. Retrieved from <https://www.eea.europa.eu/policy-documents/directive-2000-60-ec-of>
- [15] Kondolf, G. M. (2012). *The espace de liberté and restoration of fluvial process: When can the river restore itself and when must we intervene?*. In P. J. Boon, & P. J. Raven (Eds.), *River Conservation and Management* (pp. 233-241). Devon, England: John Wiley & Sons.
- [16] Piégay, H., Darby, S. E., Mosselman, E., & Surian, N. (2005). A Review of Techniques Available for Delimiting the Erodible River Corridor: A Sustainable Approach to Managing Bank Erosion. *River Research and Applications*, 21(1), 773-789. <https://doi.org/10.1002/rra.881>
- [17] Ollero A. (2010). Channel changes and floodplain management in the meandering middle Ebro River, Spain. *Geomorphology*, 117(3-4), 247-260. <https://doi.org/10.1016/j.geomorph.2009.01.015>
- [18] Rapp, C. F., & Abbe, T. E. (2003). *A Framework for Delineating Channel Migration Zones*. Retrieved from <https://apps.ecology.wa.gov/publications/documents/0306027.pdf>
- [19] Ciotti, D. C., McKee, J., Pope, K. L., Kondolf, G. M., & Pollock, M. M. (2021). Design Criteria for Process-Based Restoration of Fluvial Systems. *Bioscience*, 71(8), 831-845. <https://doi.org/10.1093/biosci/biab065>
- [20] Beechie, T. J., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., ... Pollock, M. M. (2010). Process-based Principles for Restoring River Ecosystems. *BioScience*, (60), 209-222. doi:10.1525/bio.2010.60.3.7
- [21] Kondolf, G. M., Boulton, A. J., O'Daniel, S., Poole, G. C., Rahel, F. J., Stanley, E. H., ... Nakamura, K. (2006). Process-Based Ecological River Restoration: Visualising Three-Dimensional Connectivity and Dynamic Vectors to Recover Lost Linkages. *Ecology and Society*, 11(2), 5. doi:10.5751/ES-01747-110205
- [22] Johnson, M. F., Thorne, C. R., Castro, J. M., Kondolf, G. M., Mezzacano, C. S., Rood, S. B., & Westbrook, C. (2019). Biomic river restoration: A new focus for river management. *River Research and Applications*, 36(1), 1-10. <https://doi.org/10.1002/rra.3529>
- [23] Downs, P., & Gregory, K. J. (2014). *River Channel Management: Towards Sustainable Catchment Hydrosystems*. London, England: Routledge.
- [24] DIAE (Département de l'intérieur, de l'agriculture, et de l'environnement), Canton of Geneva. (2003). *L'Aire, fiche-rivière no3 (2e édition)* [The Aire, river sheet No3 (2nd edition)]. Geneva, Switzerland: DIAE, Canton of Geneva.
- [25] Superpositions. (2018). *Aire: The river and its double*. Zurich, Switzerland: Park Books.
- [26] Group Superpositions. (2017). Designing a Rivergarden—Renaturation of River Aire, Geneva, Switzerland. *Landscape Architecture Frontiers*, 5(1), 72-83. <https://doi.org/10.15302/J-LAF-20170108>
- [27] Pfiffner, O. A. (2010). *Geologie der Alpen [Geology of the Alps]*. Stuttgart, Germany: Haupt UTB.
- [28] Rädlinger, C., Hafner, K., Junge, M., & Nebl, A. (2012). *Geschichte der Isar in München [History of the Isar in Munich]*. Munich, Germany: Schiermeier.
- [29] Neumann, A., Gabel, G., Gröbmaier, W., Kolbinger, A., Kraier, W., Krolo, M., ... Zahlheimer, W. (2011). *Flusslandschaft Isar im Wandel der Zeit [River landscape Isar in the course of time]*. Augsburg, Germany: Bayerisches Landesamt für Umwelt.
- [30] Bill, H. C., Spahn, P., Reich, M., & Plachter, H. (1997). The distribution and patch dynamics of the German tamarisk *Myricaria germanica* (L) Desv, in the upper River Isar, Bavaria. *Zeitschrift für Ökologie und Naturschutz*, 6(3), 137-150.
- [31] Döring, N., Jochum, G., Düchs, J. & Binder, W. (2010). *Die neue Isar: Renaturierung, kulturelle Öffnung und Ideen-Fluß, Geschichtliches wie Literarisches [The new Isar: renaturation, cultural opening and flow of ideas, historical and literary]*. Munich, Germany: Buch & Media.
- [32] Bäumler, K. (1988). *Heilige Kühe für die Isar anmelken [Milking sacred cows for the Isar]...* Munich, Germany: Gemeinsamer Arbeitskreis Isar der CSU-Kreisverbände Freising, Schwabing und München Land.
- [33] Heckmann, T., Haas, F., Abel, J., Rimböck, A., & Becht, M. (2017). Feeding the hungry river: Fluvial morphodynamics and the entrainment of artificially inserted sediment at the dammed river Isar, Eastern Alps, Germany. *Geomorphology*, 291(1), 128-142. doi:10.1016/j.geomorph.2017.01.025
- [34] DKRZ. (2017). *Rechnungen im Rahmen des internationalen Klimamodell-Vergleichsprojektes CMIP5 und für den fünften Klimaschutzbericht der Vereinten Nationen (IPCC AR5) [Calculations within the framework of the international climate model comparison project CMIP5 and for the fifth Climate Change Report of the United Nations (IPCC AR5)]*. Retrieved from <https://www.dkrz.de/de/kommunikation/klimasimulationen/de-cmip5-ipcc-ar5>
- [35] Wagner, T., Themeßl, M., Schüppel, A., Gobiet, A., Stigler, H., & Birk, S. (2017). Impacts of climate change on stream flow and hydro power generation in the Alpine region. *Environmental Earth Sciences*, 76(1), 1-22. doi:10.1007/s12665-016-6318-6
- [36] Zingraff-Hamed, A., Martin, J., Lupp, G., Linnerooth-Bayer, J., & Pauleit, S. (2019). Designing a Resilient Waterscape Using a Living Lab and Catalyzing Polycentric Governance. *Landscape Architecture Frontiers*, 7(3), 12-31. <https://doi.org/10.15302/J-LAF-1-020003>
- [37] Armonat, T. (2010). Isar—drei Ziele, ein Plan Eine Zwischenbilanz zum Münchener Isarplan [Isar—three goals, one plan An interim assessment of the Munich Isar Plan]. *Garten und Landschaft*, 120(11), 20-25.
- [38] Binder, W. (2010). The Restoration of the Isar South of Munich. *Wasserwirtschaft*, 100(3), 15-19.
- [39] Zingraff-Hamed, A., Lupp, G., Bäumler, K., Huang, J., & Pauleit, S. (2021). The Isar River: Social Pride as a Driver of River Restoration. In Wantzen, K. M. (Ed.), *River Culture—Life as a Dance to the Rhythm of the Waters* (pp. 609-634). Paris, France: UNESCO Publishing.
- [40] Zingraff-Hamed, A., Noack, M., Greulich, S., Schwarzwälder, K., Wantzen, K. M., & Pauleit, S. (2018). Model-Based Evaluation of Urban River Restoration: Conflicts between Sensitive Fish Species and Recreational Users. *Sustainability*, (10), 1747. doi:10.3390/su10061747
- [41] Zingraff-Hamed, A., Greulich, S., Egger, G., Pauleit, S., & Wantzen, K. M. (2016). Urban river restoration, evaluation and conflicts between ecological and social quality. In Deutsche Gesellschaft für Limnologie (DGL) (Eds.), *Erweiterte Zusammenfassungen der Jahrestagung 2016 (Wien)*. Göttingen, Germany: Hubert & Co.
- [42] Zingraff-Hamed, A., Noack, M., Greulich, S., Schwarzwälder, K., Pauleit, S., & Wantzen, K. M. (2018). Model-Based Evaluation of the Effects of River Discharge Modulations on Physical Fish Habitat Quality. *Water*, 10(4), 1-22. doi:10.3390/w10040374