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Back to the surface – Daylighting urban streams in a Global North–South comparison

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Many urban streams have vanished from the surface as a collateral effect of urban growth. Often, these buried streams have been forgotten, and only street names remind us of their existence. Reasons for stream burial include the gain of space for road or house construction or the use of stream water to transport wastewater. Today, restoration efforts to bring back fully canalized streams to the surface and to restore their stream bed (so-called daylighting) are being increasingly integrated into urban blue-green space planning, recognizing the high ecological and social value of urban streams, especially to support resilience against climate change impacts in cities. In this paper, we briefly revise the impacts of stream burial, present a series of case studies of daylighting from Europe (France, Switzerland, and Germany), and compare them with case studies from Asia (China, India, Taiwan). We found that high real estate prices, limited buffer riparian zone and resistance by the inhabitants were the greatest obstacles to stream daylighting projects. In contrast, economic gains from separating wastewater from rainwater and revival of cultural linkages with water were the strongest drivers to restore these streams. We then present methods on how to identify buried streams as candidates for daylighting and deliver criteria to select the most promising candidates. Acknowledging that each restoration project requires to be adapted to the local biophysical and local setting, we deliver a preliminary decision support system and a guideline for identifying the best candidate streams for daylighting projects, including the arguments in favor of restoration, the caveats, the social processes of decision-making, and perspectives for the integration of stream daylighting into urban climate change mitigation and adaptation concepts, in a Global North-South comparison.

KEYWORDS

buried rivers, decision support system, ecology, restoration, urban planning and design

Introduction

Streams and wetlands are rare sights in cities. This is not due to the fact that their density would be naturally lower in cities than elsewhere but rather because they have been removed or become invisible, turning cities into urban deserts (Napieralski et al., 2015). While urban wetlands were mostly drained to gain space for further urban growth, resulting in their definitive removal, thousands of urban streams were buried, i.e., placed into concrete canals and covered with asphalt. This means that it is still possible to restore these streams, to bring them back to the surface. It is the purpose of this paper to analyze literature and case studies on this issue worldwide, with a focus on Western Europe (France, Switzerland, Germany) and Asia (China, India, Taiwan), to reveal why streams have been buried, which consequences go along with stream burial and under which circumstances they can be revived.

The dramatic situation of urban hydrosystems in general, as well as options and social processes to plan and implement stream restoration projects have been presented elsewhere in due detail (e.g., Walsh et al., 2005; Palmer et al., 2007; Wantzen et al., 2019). These papers also discuss obstacles to stream restoration, which also apply to stream daylighting, such as non-point pollution, lack of technical knowledge, or uncertainties around science/practice (see also Lave, 2012). Our paper focuses on stream daylighting, i.e. the deculverting (often including the uplifting) of streambeds to the surface, which is a more recent sub-discipline of urban stream restoration (Wild et al., 2011) that requires additional efforts. Khirfan et al. (2020a, p. 10) have defined stream daylighting as "*the practice of removing streams from buried conditions and exposing them to the Earth's surface in order to directly or indirectly enhance the ecological, economic and/or socio-cultural well-being of a region and its inhabitants.*" Daylighting re-connects streams to humans and re-establishes stream ecosystem functions and services.

Since the first documented stream daylighting project in the 1970s, i.e., the Napa Creek in San Francisco Bay Area, USA (Delibas and Tezer, 2017), there has been an increasing academic interest in studying stream daylighting as a concept as well as a practice. Stream daylighting has so far gained chiefly interest in the United States (Pinkham, 2000; Trice, 2013; Neale and Moffett, 2016) and Europe (Wild et al., 2011, 2019) but it is becoming a global movement. However, related literature disperses over many disciplines and is fragmented over multiple themes. Applying a combined method of a systematic review and content analysis to 115 peer-reviewed and gray literature publications from 1992 to 2018 on global stream daylighting, Khirfan et al. (2020a,b,c,d) identified nine main themes of stream daylighting as ecology, economy, hydrology, infrastructure, politics and policy, sociocultural, built form and urban design, inclusive planning and a multidisciplinary trend of emerging daylighting studies in recent years. The same authors identified over- and under representativeness of certain issues, including a dearth of published research results from the Global South (e.g., more than half of the Asian case studies focused on Cheonggyecheon stream in Seoul, South Korea), missing linkage between stream daylighting impacts and climate change mitigation and/or adaptation, and a bias towards ecological-hydrological against social-economical themes. Usher et al. (2021) claim that there is a gap in social studies concerning daylighting.

Our paper attempts to contribute some elements to balance this bias. This study aims to deliver incentives for urban planners to integrate stream daylighting into their concepts of blue/green corridor development, climate-change mitigation and/or adaptation strategies. In the realm of urban resilience building, we tend to provide an inter-disciplinary consideration of human wellbeing, biodiversity, ecosystem services and socio-economic processes. We especially want to encourage urban planners in fast-growing cities, i.e., in the Global South, to avoid further stream burial, leave behind the dependency on previous decisions and processes, and enter new terrain.

This work is organized along a logical sequence from analyzing the causes and consequences of stream burial to the decision making processes about which streams to select for a daylighting project. The first part describes the trends and specific effects of channelization compared with other urban impacts on streams. Then we present a series of case studies of daylighting projects with their specific social and environmental settings in Europe and Asia. Specifically, we elucidated the historical background, the social-ecological motivations for daylighting, the challenges and problem-solving, and finally, the lessons that can be learned from these projects. In the third section, we describe some methods of identifying buried streams and potential candidates for stream daylighting projects based on historical maps. In the fourth and last part, acknowledging that each restoration project requires to be adapted to the local biophysical and local setting, we try to approach a decision support system (DSS) as a guideline for future stream daylighting projects, identifying the arguments in favor of restoration, the caveats, the social processes of decision-making, and perspectives for the integration of stream daylighting into urban climate change mitigation concepts.

Research method

This study combines information from case studies and practical, long-term expertise with stream daylighting projects by some authors (FK, ML, NG, and MS) and interviews by TP at the French Biodiversity Agency. We acknowledge that the descriptive character of the individual cases does not allow an in-depth comparison on all criteria requested in social sciences method papers (e.g., Hantrais, 1999; Mangen, 1999; Backer, 2009; Pierre, 2014), however, we have also faced the problem that interdisciplinary methods involving comparative aspects of biophysical, cultural, engineering, and political sciences at the same time are still in their infancies. Moreover, due to the lack of a global, systematic and interdisciplinary effect-monitoring protocol for river restoration projects (see, e.g., Wantzen et al., 2019 for discussion), we also have to acknowledge that some case studies provided information that was not available for other sites. Thus, this article is not a systematic review (but see Khirfan et al., 2020a,b,c,d), rather, it develops suggestions for re-establishing hydro-social connectivity in urban streams in a Global North/South perspective.

The selection criteria for the case studies included (i) new or yet little known studies (based on reports in the languages of the respective countries), (ii) access to site managers that provide first-hand suggestions from their long-term experience, (iii) representative projects for different social-geographical contexts, and (iv) geographical sites allowing to provide a Global North/South comparison. We focused on case studies in Europe (as an example for the Global North) that were not or only partly documented in peer-reviewed journals and on Asia (as an example for the Global South, where in many countries currently a societal shift toward daylighting takes place). We could not (yet) find well documented projects from other fast-developing cities in Africa and Latin America.

Causes and effects of stream burial and trends in daylighting

Vanishing streams

As with other human impacts on flowing water systems, stream burial began much earlier in the Global North than in the Global South (Wantzen et al., 2019; Khirfan et al., 2021). In most of Western Europe, the peaks of urbanization (and their consequences on aquatic socio-ecosystems) took place in the mid-19th and mid-20th centuries (Wolf et al., 2021; Lestel et al., 2022). Most buried streams have disappeared from the maps (Adam et al., 2007) despite their number being significant, especially headwater streams. In the headwater area of the Moselle River (France), 41% of the total length of streams became canalized (Le Bihan, 2009). Similar developments occurred in the North America (see Khirfan et al., 2021 for a global review), e.g., in Baltimore City (USA), 66% of all streams were buried (Elmore and Kaushal, 2008). In the Global South, stream burial is subject to similar drivers as in the Global North, however, the enormous speed of urbanization in the past decades (United Nations, 2019) has caused a superposition of different impacts on urban hydrosystems, which further complicates their restoration, among other problems (Wantzen et al., 2019 and see case studies below).

There are several reasons why urban planners decided to canalize streams. Rather than being perceived as a valuable ecosystem, the murky, malodorant waters of already-polluted urban streams generally provoke negative emotions and are often considered a menace to public health. The dynamic nature of meandering streams sets real estate values at risk, and many streams became buried to gain space for further urban projects. The classical feature is to canalize streams and combine them with the sewer system below the roads, with the practical side-effect that the nuisance of polluted water is out of sight. The stream water can be used to carry away human wastewater, and the former riparian floodplain provides easily constructible urban space (Broadhead et al., 2013; Wantzen et al., 2019; **Table 1**). As a result, the public memory of the precedent situation (open streams) and the relationships with the stream, the river culture (Wantzen et al., 2016), or social connectivity (Kondolf and Pinto, 2017) have been widely lost in cities. Especially in fast-growing cities, the growing socio-cultural disconnection between humans and urban streams reduces the motivation of citizens to support restoration projects (Wantzen et al., 2019).

Socio-ecological effects of stream burial

Natural streams are highly dynamic ecosystems with a high spatial-temporal diversity of geomorphological, chemical, and biological patterns and processes (Giller and Malmqvist, 1998; Allan et al., 2021). Maybe their most striking elements are the patchy mosaic of microhabitats, allowing high biodiversity in limited space, and pulsing and/or spiraling biotic/biogeochemical processes at the aquatic-terrestrial and surface-groundwater interfaces (Newbold et al., 1982; Pringle et al., 1988; Ward, 1989; McClain et al., 2003; Wantzen and Junk, 2006), as well as their reciprocal relationships

TABLE 1 Arguments that have commonly been used to justify stream burial (based on reviews by Broadhead et al., 2013; Wantzen et al., 2019).

Category	Causes for stream burial
Human activities	Gain available space
	Increasing urbanization
	Recreational activities
	Road or parking constructions
	Industrial activities
Water pollution	Hide pollution
	Hide bad smell
	Flush away wastewater
Fears	Reduce the risk of flooding

with the surrounding terrestrial food webs (Nakano and Murakami, 2001). Riparian zones and their vegetation act as hydrological buffers, absorbing flood water and releasing it during dry periods. Independent of whether their food webs were mainly driven by in-stream primary production or by allochtonous detritus (e.g., leaf litter from riparian trees), stream ecosystems depend on sunlight, setting the pace for all biological processes and life cycles of their biota. Streams thereby provide essential ecosystem services (Bolund and Hunhammar, 1999; Jähnig et al., 2022).

Humans are socially and culturally connected to streams and rivers (Wantzen et al., 2016) especially in cities (Kondolf and Pinto, 2017; Wantzen et al., 2019), and the memory to these linkages may be maintained even if the streams had been buried (see section "Historical analyses to rediscover buried streams" of this paper). Streams and other hydrosystems improve the ecosystem functions of the urban ecosystems and support human health and psychological wellbeing, specifically to spiritual healing, relaxation, inspiration, sense of place, and quality of life (see review by Zingraff-Hamed et al., 2021). All these characteristics and ecosystem services depend on their hydro-morphological dynamics, i.e., the ability to change the physical shape of habitats under the influence of environmental flows (see Arthington et al., 2018) and their physical connectedness to the lateral stream banks, the hyporheic zone below the stream and the open air and sunlight above it. And they all change dramatically when streams are transformed to be compatible with solid urban structures.

Compared with the classical "urban stream syndrome," i.e., the consistently observed ecological degradation due to surface sealing and channelization of urban streams (Walsh et al., 2005; Bernhardt and Palmer, 2007) or the "urban hydrosystem syndrome," which further involves social, political and global aspects (Wantzen et al., 2019), the impacts of stream burial go deeper, as many of the ecological and social features of a stream described above virtually vanish when it gets buried (**Figure 1**).

In most cities, stream burial (culverting) is often associated with flood risk management, however, under a changing climate, underground culverts with limited drainage capacity are proved not to be able to deal with the increasing extreme rainfall events (Wild et al., 2019). In addition, culverted streams and springs often flow in combined sewers, increasing the clean baseflow but reducing sewer capacity and increasing wastewater treatment costs (Broadhead et al., 2013; Chou, 2013). They may also introduce sediment and debris (Wild et al., 2011) or alter the sewage chemistry (Broadhead et al., 2013). A case study in a water-scarce city, Amman in Jordan, revealed such specific consequences of stream burial: the loss of regulatory and socio-cultural ecosystem services (Khirfan et al., 2021).

The primary ecological effect of the burial is the loss of light, which affects all processes based on primary production. Combined with the interruption of transversal connectivity (to the riparian zone that could contribute leaf litter and important ecological processes), the basis for food webs is interrupted. Heterotrophic processes become reduced to bacterial processing of particulate organic matter that could pass the grids upstream of the entirely tubed section. Urban surface runoff generally contributes grit, silt, tire wear particles or other toxic substances to the buried stream system, which all have negative effects on the biota (and may create flow obstacles). On the other hand, if the buried streams are connected to the wastewater system, they receive other kinds of organic inputs, and the water chemistry is changed by increased inputs of oxygen-demanding substances (bacterial biomass, labile carbon) and nutrients (nitrate, phosphate), which reduce the occurrence of typical cave species and favor pollution-resistant consumers (e.g., microbes and protozoans in biofilms). Lack of biologically active surfaces, reduced retention time, and disconnection from the hyporheic zone reduce the self-purification capacities of buried streams and increase nitrate export from the catchment (Beaulieu et al., 2015). While fish and some invertebrates may still use the shaded zones at the entrance or outlet of the channelized section, most species avoid the permanently dark inner parts, and fish species are prevented from crossing this section (Elmore and Kaushal, 2008). A detailed analysis of the effects of the 1880 m-long covering of the 15 m-wide Nahe stream (Idar-Oberstein, Germany) has evidenced that despite sufficient oxygen saturation of the water, the abundance of macrozoobenthos species dropped by 50–80%, species diversity was reduced by 20–34% and some functional feeding groups (mostly, grazers and filter-feeders) were strongly reduced. Many characteristic invertebrate and fish species were abundant in the reference sections but lacking in the tunneled zone (Brunke et al., 1994).

Benefits of stream daylighting

Stream daylighting can be motivated by different arguments (**Figure 2**). More and more cities discover that critical ecosystem services once delivered by streams have been lost with

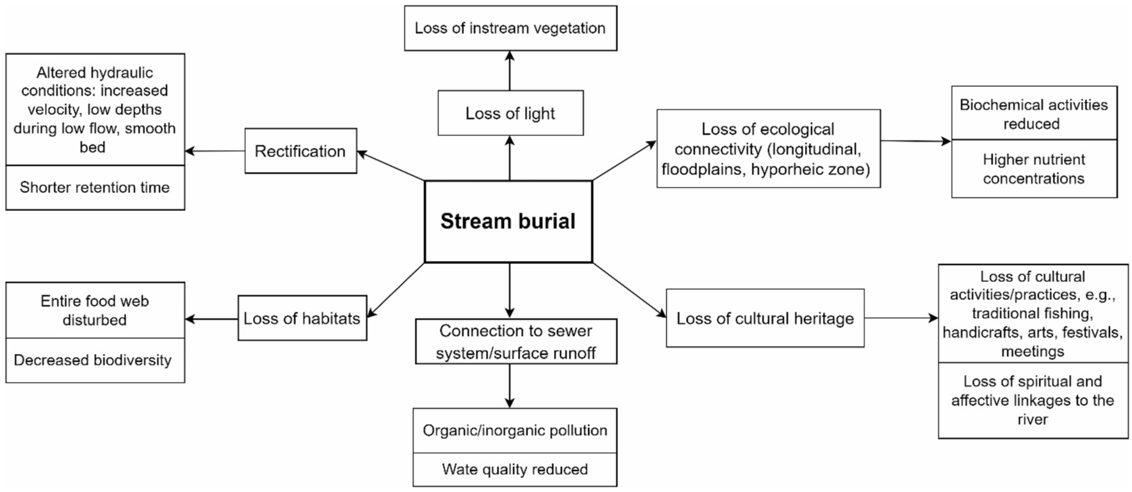

FIGURE 1
A synthesis of impacts caused by stream burial. See text for citations.

burial. Daylighting may reverse the negative impacts described above (see also review in Khirfan et al., 2020a). Although buried streams do not figure in the habitat mapping such as the European Framework directives on Water or Fauna-Flora-Habitat (Hering et al., 2010), their restoration projects are acknowledged as measures favoring biodiversity, which facilitates financial support by the European Union. Many urban planners are attracted by the aesthetic value of daylighting to make their city more attractive for investments and tourism. As Usher et al. (2021, p. 1) put it, "*daylighting can unleash the social 'stickiness' of water, its proclivity to draw and bind together, to revitalize the park, enhancing connection to wildness, attachment to place and sense of community.*" And in spite that daylighting projects figure among the most cost-intensive restoration schemes, there are still direct economic arguments in favor of their implementation. Mixing surface water and wastewater produces elevated costs in wastewater treatment plants, which can be significantly reduced by daylighting (see Zurich example below). In the context of climate change, the restored urban streams, as an essential green infrastructure of Nature-based Solutions (Cohen-Shacham et al., 2016), can be more cost-effective compared to traditional engineered alternatives for disaster risk reduction (Keesstra et al., 2018; Seddon et al., 2020) and offer social co-benefits (Cohen-Shacham et al., 2019).

Case studies of daylighting from Europe and Asia

Stream daylighting projects are being increasingly acknowledged as an important element of re-establishing natural elements in cities (Khirfan et al., 2020a; Usher et al., 2021). In analogy to the earlier analysis of open urban hydrosystems (Wantzen et al., 2019), our case studies from Europe and Asia were selected to enable a Global North-South comparison. In Europe, both, environmental degradation and restoration projects have begun earlier (but with a time lag of 100–200 years in between), yet, environmental problems of urban streams are far from being solved (Booth et al., 2016). In Asia, both these processes occur synchronously and are often initiated by different drivers than in Europe.

The general measures that were taken to revive and daylight streams in our case studies are summarized below (**Table 2**) and specific projects are described in the respective case studies (**Tables 3–6**). Practical actions can be divided into the stream daylighting as such (removal of the concrete cover and of the canal profile, heightening of the stream bed) and the stream restoration measures also known for unburied streams, i.e., the diversification of habitats, in-stream substrates, and bank structures, widening of the streambed and the riparian zone.

France: Periurban daylighting

Historical background

One of the most famous cases of urban redesign worldwide was the transformation of Paris under Napoleon III by the engineer Baron de Haussmann in the 19th century (Kirkland, 2013). In this context, a sewer system was established that included the burial of many urban streams (Gandy, 1999), which can be visited in a dedicated museum[1]. Today, the French Biodiversity Office (OFB) monitors and supports restoration projects and provides a database of case studies (Eau et Biodiversité, 2021), including stream daylighting. Currently, six

1 https://musee-egouts.paris.fr/

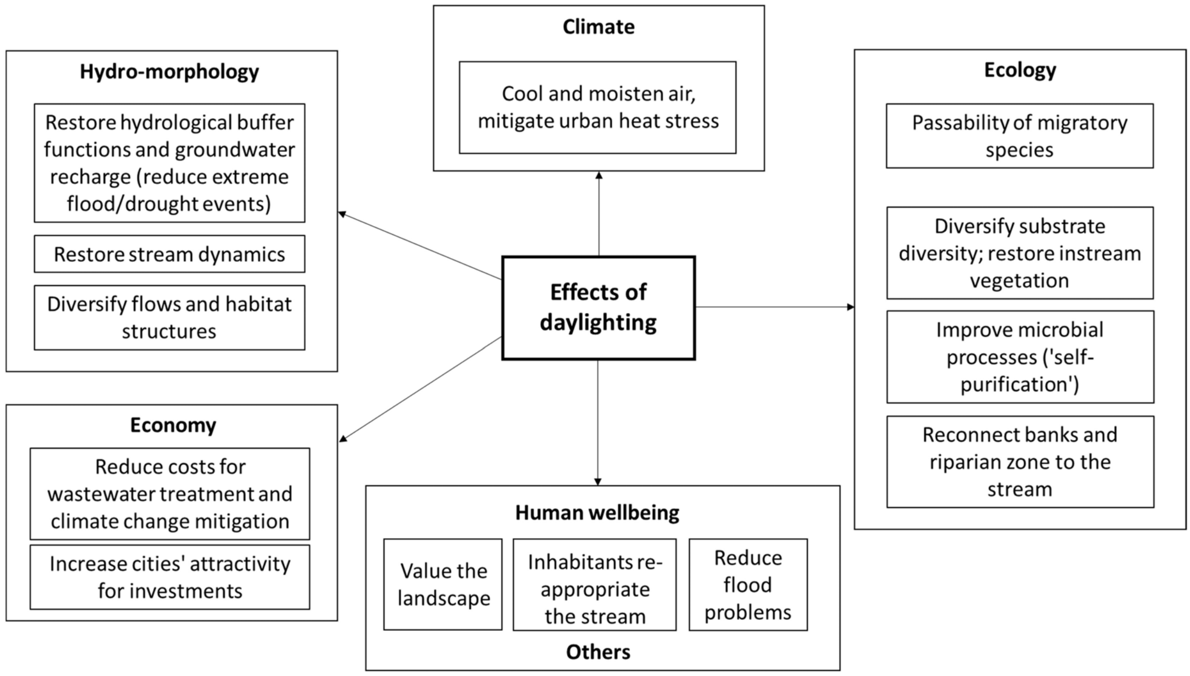

FIGURE 2
Benefits of stream daylighting. See text for citations.

projects are registered in France, between 50 and 280 m long, with average costs of 320–2,600 € per restored meter of the stream (see **Table 3** and see **Supplementary Annex I** for a details).

Social-ecological motivations for daylighting

The main motivations driving French daylighting projects were related to ecological aspects, in order to improve the ecological quality of the stream, in the context of the European directives on water (WFD), floods, and groundwater. The WFD imposes for each member state to reach a good ecological status for all water bodies and re-establish environmental flows (European Commission, Directorate-General for Environment, 2016). This legal framework has been integrated into French legislation i.a., in the "Grenelle" laws on environmental protection (Whiteside et al., 2010), the water law, and the French institution dealing with combined aquatic environment management and flood prevention (GEMAPI, 2021).

The primary objectives for the communalities and cities leading the projects mentioned above, however, were social aspects, such as the reduction of flood risk and increasing the attractivity of the stream for citizens (for a detailed analysis of societal drivers for general urban river restoration in France, see Zingraff-Hamed et al., 2017).

In the case of the Bièvre (Seine-Normandie), the project was driven by an improvement in wastewater treatment. Full channelization was not necessary anymore, and the local population (and the mayor) wanted the stream to return to the city as a part of a leisure area (Fernandez, 2017; AFB, 2018). The stream has been disconnected from the sewage network, the old asphalt road that had covered the stream was removed, and a cycling/hiking path next to the restored stream was established (**Figure 3**).

In two other cases, the Redon and Sonnette streams, detailed monitoring of the ecological and social effects has been performed (**Table 3**; Laetitia Boutet-Berry, OFB, personal communication to Piednoir, 2021). Despite the relatively short monitoring period after daylighting, an increase in biodiversity was noticed, but the water quality remained low. Moreover, the longitudinal connectivity has been re-established, resulting in the return of some migratory species. The habitats and flow patterns were diversified, and the bottom substrate was less clogged. With daylighting, the urban landscape aspect was improved, which resulted in an increased attractivity of the sites and their reappropriation by the residents.

Challenges and problem-solving

In the case of the Sonnette, the local people first had opposed against the project. They had a living memory to an ancient factory, which had provided a number of employments in the past. The original plan of the project had foreseen to demolish the entire complex, which provoked resistance by the locals. After public debates, a compromise was found, maintaining an old washhouse building and giving it a new usage. This resulted in the appreciation of the restoration measures by the local population.

TABLE 2 Types of actions performed during the daylighting of streams in the case studies.

	Type of actions performed
Daylighting (s.s.)	Removal of the culvert
	Removal of lateral channel walls and covering
	Old covered channel maintained and a new one created
	Wall materials partially retained and reused for channel and bank structures
	Replacement of the culvert by a bridge
Main channel	Creation of a new main channel
	Maintenance of the old stream bed after decoupling from the sewer system
	Let the stream naturally retrace its channel (natural reconstruction)
	Creation of a sinuous channel with fixed meanders
	Reconstitution of a natural confluence
	Introduction of natural substrates on a sealed stream bed
	Sediment recharge in natural stream bed
	Installation of stony current deflectors, tree stumps, or artificial rapids to diversify the flow
	Plantation of aquatic and semi-aquatic plant species
	Creation of a block ramp for fish migration
	Increase the water depth to improve the flood prevention
Banks	Restoration of natural slopes
	Permit natural erosion/sedimentation
	Stabilization by gabions, fascines, bedrock or geotextile made of coconut fiber
	Stabilization and protection (banks and bank foot) by green engineering techniques
	Replant macrophytes and riparian forest
	Allow natural succession of vegetation
Other	Removal of sewage inflow
	Shaping of floodable, vegetated, and erodible terraces
	Dismantlement of buildings
	Creation of a bypass river to cope with flood water

In our case studies (**Table 3**), different stakeholders were involved in stream restoration, including individual citizens, NGOs such as fishing federations and conservationists, the municipality, the department, and national institutions [*l'Agence française pour la biodiversité*, AFB, renamed l'Office français de la biodiversité (OFB) in 2020]. Smaller municipalities often join forces to form an administrative syndicate, but they remain important in the process as they generally purchase the real estate of the sites where the project takes place. These two types of stakeholders often have different interests and motivations, e.g., intercommunal syndicates may want to focus on the environmental benefits while municipalities may be interested in the architectural and landscape aspect. Drivers for the projects were, apart from individual initiatives, management plans (often in the context of flood risk reduction), or a so-called river contracts (*contrat de rivière*), which are a private-public-partnership in the context of a basin-wide management scheme (SAGE, *schéma d'aménagement et de gestion des eaux*) (Allain, 2001). River contracts are a traditional juridical instrument, originally meant to share fishing resources equally, but today, they are important elements for conservation and restoration. The decision process includes a field visit, a feasibility study, a concertation phase with the citizens, and finally, a management scenario. Thus, the daylighting project often develops from a purely environment-focused to a global project with different organizations involved in its implementation. Finally, the legally binding authorization procedure is fixed in form of a declaration of general interest (DIG, *déclaration d'intérêt général*) or a prefectural decree. Following implementation, the maintenance mostly concerns the control of vegetation, both inside the stream and in the riparian zone.

Lessons learned

Most projects were well communicated by the media, explanatory field visits and a decent technical documentation, written in a clear language and easily available to the public (see **Table 3** and **Supplementary Annex I**). This tends to facilitate the launching of other projects of this kind. Acknowledgment of the "hybrid" character of the urban stream being both, a biophysical ecosystem and a social element has been found to be crucial for decision-making for restoration in France (Lespez et al., 2022).

Switzerland: The Zurich stream daylighting program

Historical background

Several smaller projects of stream headwater daylighting, with similar foci as in France (mainly to re-establish fish migration) have been performed in Switzerland, and the employed techniques were documented in detail (e.g., BIOTEC, 2017, 2019). Moreover, the city of Zurich is one of the global pioneers in daylighting urban streams (Broadhead et al., 2013). The "The Zurich stream daylighting program" even received the Water Award Switzerland (Gewässerpreis Schweiz) in 2003 (Conradin and Buchli, 2004). Zurich is a big city in European terms, with more than 400,000 inhabitants in the city center and one million in the agglomeration. It has about 130 km of public running waters, with 63 km of it running through forested or open landscape and 67 km in the urbanized area. In this urbanized area, 40 km of streams are running open, whereas 27 km were fully channelized. These streams were buried into underground pipes, mostly during the late 19th and early 20th centuries, when the most intensive phase of urbanization was taking place. The reasons were mainly to increase space for road and house construction and to reduce risks of flooding and pollution. Some streams were culverted to flush away wastewater and were connected to the 1,000 km long sewage system. However, the combined system transporting sewage and residual water (surface runoff, rainwater, groundwater seepage into the canalization etc.) produces high costs, as wastewater treatment plants have to deal with unpolluted or slightly polluted runoff resulting in less efficient purification. Broadhead et al. (2013) estimated that 7–16% (up to 54%) of the sewage baseflow was steady intrusion of residual water. Sewage and residual water sum up to about 70 Mio m^3/year (corresponding to 150,000 m^3/day or ∼1,700 L/s). If these waters were not separated, they would become treated altogether with the highest technological standards, including ozonation and sand filtration. Every liter of unpolluted residual water that enters the sewage system per second was estimated to cause additional annual costs of about 5,000 € (for example, 200 L/s result in additional annual costs of 1,000,000 €; Conradin and Buchli, 2004).

Social-ecological motivations for daylighting

Before initializing the daylighting project, only 20% of the residual water was treated separately from the wastewater. As a result of daylighting and separating wastewater and residual water between 1985 and 2017, the quantity of treated residual water could be reduced from about 850 to 400 L/s on average, corresponding to economic savings of about 2,250,000 € per year. The total costs invested for the daylighting project were estimated to be 30,000,000 € and its maintenance costs to 1,000,000 € per year (Conradin and Buchli, 2004). These figures suggest that the program had fully amortized within 15 years, followed by a long phase of generating economic gains by reducing the annual budget of the city of Zurich. Even considering that the calculation was simplified (i.e., ecosystem services had not been quantified, annual discharge volumes may vary, etc.), the economic argument was clearly an important driver for channel reopening projects in the 1980s and 1990s (see also Broadhead et al., 2013 for types of costs that may arise from stream capturing).

In addition to the economic argument explained above, the program was developed in a period of great environmental awareness and economic prosperity in the entire Central Europe. Despite being a water-rich country, Switzerland has early taken steps to protect its environment, specifically the alpine hydrosystems, which are highly threatened by inadequate water use (e.g., stream eutrophication due to dairy cattle herding) and by climate change (most alpine streams undergo high erosion risks, Brighenti et al., 2019). The Swiss water protection law was adopted in 1991 and stipulated that the stream water should be connected to the groundwater (Conradin and Buchli, 2004). The municipality of Zurich has anticipated this law via a decree to take actions in favor of nature and started its stream restoration and daylighting program as soon as 1985. Once the first projects had been successfully implemented, public interest was mobilized by a series of organized hiking tours along the revitalized streams. Another important element for bringing up urban restoration projects in Switzerland is the direct democracy in this country, resulting in the high participation of the citizens in the political process. Most of the actions took place in the periurban zones, where the measures could be taken more easily due to lower real estate costs (Conradin and Buchli, 2004). Many garden owners even offered their private space to remodel the reborn streams. The active engagement of citizens in so-called "Quartiervereine" (neighborhood associations in urban quarters) was very important for both, to mobilize the local citizens, and to offer space for urban waters in the parks of the public buildings and kindergartens that they manage (Stadt Zürich, 2020). The neighborhood associations organize and support activities with a local connection in culture, history, and integration, and they make a significant contribution to the quality of life in the neighborhoods. They also communicate between different cities all over Switzerland. These associations are an important link between the citizens and the local administration, and they are an expression of participative management (Stadt Zürich, 2020), which could serve as an example for other countries.

Today, more than three decades after initializing the Stream Daylighting project, the city of Zurich has separated surface water from the sewage channelization in 30 streams, which corresponds to a length of 25 km, and restored 12 open but heavily modified streams, at a length of 15 km, and finally daylighted 62 previously tubed stream sections which correspond to a length of 19.6 km (see **Supplementary Annex III**).

The program was considered to be a success not only in economic aspects, but also provided social, biological, chemical, and physical benefits (Conradin and Buchli, 2004). Since 2007, all streams have been registered in an online databank, serving as a common base for all stream management projects, integrated into a generic GIS system for the entire urban planning. All technical, administrative and juridical information in the context of "stream revitalization" is available on a public server[2].

Challenges and problem-solving

The administrative organization of the projects required efficient communication between specialists from most different areas of expertise, who, in some cases, met for the first time. Finding a common language was therefore the greatest challenge. To tackle this, a thematical working group ("Zurich Brook-Team") has been established with foci on (i) science (e.g., hydrologists, biologists, sociologists, engineers), (ii) finance, (iii) juridical details, (iv) information management and public relations, (v) permissions by the county, (vi) financial support, and (vii) details about site accessibility and land tenureship (Kari, 2004). The team built up an interdisciplinary forum, which arranged the planning and the projects as well as their maintenance by regularly exchanging knowledge, demands,

2 https://maps.zh.ch/

TABLE 3 Daylighting projects in France, registered by OFB (Eau et Biodiversité, 2021, see Supplementary Annex I for details).

Name of stream (basin)	Stream section	Project motivation	Sector length (m)	Restoration cost/m (€)	References
Le ru d'Orval (Seine-Normandie)	Headwater	Reduce flood risk, improve landscape aesthetics, restore aquatic habitats	75	320	Agence Français de la Biodiversité [AFB], 2010
Redon (Rhône-Méditerranée)	Middle section	Restore longitudinal connectivity, especially for lake trout (*Salmo trutta*)	230	400	AFB, 2012a
Le Trégou (Adour-Garonne)	Headwater	Maintenance of agricultural uses on the site. Improve hydro-morphological functioning of the watercourse	50	723	AFB, 2012b
Ruisseau de Cubes (Loire-Bretagne)	Headwater	Restore longitudinal connectivity for fish, promote recreational activities, improve the landscape aesthetics of the town center	140	984	AFB, 2016a
Sonnette (Adour-Garonne)	Plain	Improve the landscape aesthetics; secure the site; restore longitudinal connectivity	280	395	AFB, 2016b
Bièvre (Seine-Normandie)	Middle section of a lowland stream	Enhance the aesthetic aspect of the river by creating a park; diversify stream habitats	200	2600	AFB, 2018

TABLE 4 Daylighted streams in the German case of Lake Phoenix in Dortmund-Hörde with motivation, size and costs (original data by Emschergenossenschaft).

Name of stream (basin)	Type of habitat	Motivation for restoration	Sector length/ breadth (m)	Restoration cost (€)
Emscher stream	Upper section	Part of the Emscher restoration project	ca. 2000 m	230 Mio. (combined budget for flood retention, marketing of the real estate, federal, national, and EU funding)
Hörder stream	Lower section		ca. 500 m	
Lake Phoenix	Artificial mesotrophic shallow lake, disconnected from the river Emscher	Multi-purpose lake-site: biodiversity, flood retention (235,000 m^3), recreation, businesses, housing	1230 × 310 m, depth max. 4.6 m (24 ha)	

and opportunities. Many topics had to be coordinated, including flood prevention, recreation, urban development, human living environment, biotopes, and urban drainage. Furthermore, five departments within the municipality of Zurich collaborated for the many interdepartmental tasks like the implementation of public works, development of general principles for spatial planning and details for designated use, site preservation, guidelines for ecology, and maintenance tasks (Stadt Zürich, 1993).

Lessons learned

After launching this integrated stream restoration concept ("Bachkonzept") in Zurich, analysis and review were made concerning success control of planning, maintenance, and ecological effects (Stadt Zürich, 1993; Hugentobler and Gysi, 2002), and later, the technical details of the individual projects were presented in detail, including ancient maps and localization of culverted streams (Entsorgung + Recycling Zürich, 2003). As a result of public campaigns and informative walks organized by the city, the public acceptance of open brooks and streams is very high, and the streamside trails are used for recreation, jogging, bicycling etc. (Stadt Zürich, 1993).

The practical suggestions developed by a group of practitioners from Switzerland, Germany, and Austria (DVWK, 2000; Kari, 2004) include that daylighting projects should (i) be as close to natural structures as possible by integrating existing vegetation structures, allowing individual characteristics of each stream, (ii) possibly follow its original course, which often has to be redrawn after historical maps, (iii) give priority to reopening entire stream corridors to provide migration corridors for the fauna, (iv) give specific attention to the re-entry zone of an open stream into the channelized section (i.e., grids for driftwood retention should not harm migrations of amphibia), and (v) in the presence of porous bed sediments near built space, stream

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TABLE 5 Some of the recent examples of stream burial and daylighting in China.

City	Name of the stream	Daylight or burial	Motives	Objectives	Time	Sector length	Cost (€)	References
Shenzhen, Guangdong province	Yutian River	Daylight	CSOs (combine sewage overflows) cause black odorous water bodies, over 20,000 m^2 of unauthorized construction over the river channel, Sponge City policy	Water pollution control, urban river landscape improvement, create a Shenzhen version 'Cheonggyecheon'	2019, for 15 months	2.7 km	4.9 million	Chen and Hu, 2019; Water Resources Bureau of Shenzhen's Guangming District, 2019
Suzhou, Jiangsu province	Zhongjiaxiang River	Daylight	Water quality decline, decreased drainage capacity	Inherit the water culture of Suzhou 'Water City' and 'Jiangnan Water Lane'	2017–2020	349 m	2.4 million	Han, 2020
Wuhan, Hubei province	Xunsi River	Daylight	CSOs, degradation of ecological functions, migratory catfish cannot pass through the box culvert, risk of flooding in surrounding urban areas, Sponge City policy	Water pollution control, connection to the Yangtze River, ecological restoration, flood resilience enhancement, create a riverfront park, "flowing river landscape"	2019–2021	1.6 km	No data	Water Resources Bureau of Wuhan, 2019
Wuhan, Hubei province	Jiatao River	Burial	Waterlogging	Improve drainage capacity	2016–2017	6.9 km	No data	Wuhan Zhongxin Municipal Construction Co., Ltd, 2016
Yueyang, Hunan province	Zhanbei stream	Burial	Water pollution induced by domestic wastewater that discharges to the open channel	Improve water quality, intercept the domestic sewage	2017–2019	814 m	No data	He, 2018
Cangzhou, Hebei province	Dalangdian stream	Burial	Water pollution in Dalangdian reservoir, the main water supply for Cangzhou City	Improve water quality and increase water supply	2019	1.45 km	13.4 million	Cangzhou City Municipal Commission of Development and Reform, 2019
Laohekou, Hubei province	Hongchengmen moat open channel	Burial	Water pollution caused by garbage accumulation	Water pollution control	April 2020–May 2020	90 m	No data	Laohekou Municipal Government, 2020

TABLE 6 Daylighting projects in Taiwan.

Name of the stream (basin)	Stream section	Project motivation	Daylighting length (m)	Restoration cost/m (€)	References
Laojie stream	Middle section of a lowland stream	Improve flood management, water sanitation, and landscape of the river	725	45,000	Chou, 2016; Huang, 2018; Environmental Protection Administration, 2020b
Yunlin stream	Middle section of a lowland stream	Improve flood management, water sanitation, and landscape of the river	895	30,000	Yunlin County Government, 2017
Green stream; Liu stream	Middle section of a lowland stream	Improve flood management, water sanitation, and landscape of the river	430 (230 + 200); 300	–	Wang, 2015; Chen, 2019

FIGURE 3
The Bièvre before (date) and after (date) daylighting. Photograph: Hervé Cardinal- SIAVB.

beds should be sealed to avoid unwanted infiltration into the ground.

In terms of the water quality, these authors suggest that streams may receive additional donations from clean surface runoff and even rainwater from roofs. However, the dotation of surface runoff diverted to the stream should not be higher than 3–5 fold amount of base flow, and excess water should still be directed into the channelized sewer system. Even though, in the Zurich case, up to 90% of the total discharge could be spared from passage through the wastewater treatment plants.

The experiences from the Zurich project in terms of the management (**Figure 4**) have been synthesized by Loritz et al. (2016) who suggest to (i) timely integrate the elaboration of maintenance plans into the project planning (including regular updates documenting the eventual change of status), (ii) use typical regional species replantation of riparian vegetation, avoiding fast-growing or spreading plant species, (iii) consider the continuity of maintenance in financial and personnel planning (in Zurich, maintenance costs of 55 km streams within the urban perimeter and 40 km streams outside the urbanized space amount to 1 – 1.4 Mio €/a), (iv) create awareness (among workers and the public) that the entire stream corridor, including its riparian zone, should be considered a functional unit (and that moderate flooding of the riparian zone or plant debris should be considered as a "normal"), (v) stream and pedestrian walkways should be connected to facilitate accessibility and to increase human well-being, and (vi) consider that each stream has its individual characteristics with a variety of parameters, there is no "one-size-fits-all" solution.

In summary, the stream daylighting project in Zurich has turned out to be a great success, which may be attributed to the strong engagement of stakeholders and the timely issuing of the water protection law. All the decision-making stakeholders were involved, with an early approval of the program by the city administration and an interdepartmental task force to coordinate activities, and with constant information to the public, which was also actively engaged.

Germany: Post-mining Emscher urbanscape in the Ruhrgebiet

Historical background

The Emscher basin, located in the federal state of North-Rhine Westphalia, Germany, has experienced a century of intensive mining, steel industry expansion, and population growth. Subsidence of the ground caused by mining impeded a closed wastewater system, so that the Emscher River became

FIGURE 4
Technician cleaning the grid of the entry of the culverted section of an urban stream. Photograph: Karl M. Wantzen.

transformed into an open sewer network by straightening the river and its tributaries and laying them in concrete beds and dikes. Due to subsidence, only some stream sections, restricted to the urban and industrial centers, had been culverted. After ending the mining activities in the 1970s, a huge project, with costs summing up to more than € 5.6 billion, was performed to build a modern underground sewage network and to restore the whole river network of the Emscher basin towards near-natural conditions from 1990 to 2021 (Gerner et al., 2022).

In this context, two streams could be daylighted in Dortmund's city district "Hörde" recently (**Figures 5**, **6**). The first example is the "Hoesch Kanal" that had been built in 1923, in 8 m below the surface underneath the steel plant "Hermannshütte." It served as a mixed sewer and a conduct for the entire discharge of the Emscher River over a length of 2 km. The second example, the small stream "Hörder Bach" at the western end of the district, had also been buried in around 1920 during the construction of the "Hermannshütte."

Social-ecological motivations for daylighting

From 2001 to 2004, the then-obsolete steel factories were sold and dismantled, and the city of Dortmund acquired the area. In discussions about the future use of the area, the idea of the *de novo* construction of an artificial, multi-purpose lake surrounded by newly built properties was proposed (**Figure 6**). Thus, the daylighting project was integrated into a larger project to completely redesign an abandoned urban brownfield site, driven by the European Water Framework Directive, which also included the restoration of uncovered but canalized streams and a complete separation of sewer conducts and streams (**Figure 6** and see Gerner et al., 2022 for a review).

Challenges and problem-solving

A series of interviews conducted as part of the EU-funded project DESSIN (DESSIN, 2014; Anzaldua et al., 2016) identified that initially, the suggestion to construct a new lake was considered too ambitious; however, a few committed individual actors brought the project forward and made important first steps towards a feasibility study and a public discussion. The combined development plan fulfilled diverse needs of urban planning at the same time, including the creation of a biodiversity hotspot, a flood retention basin, sites for local recreation, new areas for housing and living, and it made the city more attractive for business investments by upgrading a previously problematic district (Anzaldua et al., 2016; Rouillard et al., 2016; Gerner et al., 2018, 2022).

These arguments finally convinced the local actors and decision-makers. The Emschergenossenschaft water board coordinated the construction and management of the Emscher, the stream daylighting, and the lake construction. Public participation was realized with formal and informal meetings and discussions accompanying the entire project cycle. For the conflicting goals, compromises were found, for instance in the conflict between the ecologically required size for the lake and the Emscher stream and the desired real estate area (**Table 4**) (DESSIN, 2014; Anzaldua et al., 2016; Rouillard et al., 2016).

After a long planning phase, operations started in 2006 and both streams have been daylighted and were fully restored in 2009. For the daylighting and restoration of the Emscher river (**Figure 7**), sufficient space was available on the former steel plant site between the lake and the planned housing area to create a more natural riparian corridor for ecological development and flood protection. Quite differently, the daylighting of Hörder stream took place between an existing housing area including a castle listed as historical monument. Here, by removing a part of the street, a narrower and more artificialized corridor could be established and at the same time, bottom windows allowing the view to underground parts of the castle were integrated, combining ecological with built heritage (**Figure 8**). Care was taken that both streams flow besides the lake to avoid siltation and eutrophication of the lake (Johann and Hartung, 2021).

Lessons learned

Today (2022), the restored area has become very popular for recreation. It created jobs, and represents an urban ecological hotspot (Möhring, 2014; Rollinghoff and Westphal, 2016). Regular monitoring reveals 'good ecological potential' of the streams according to the EU

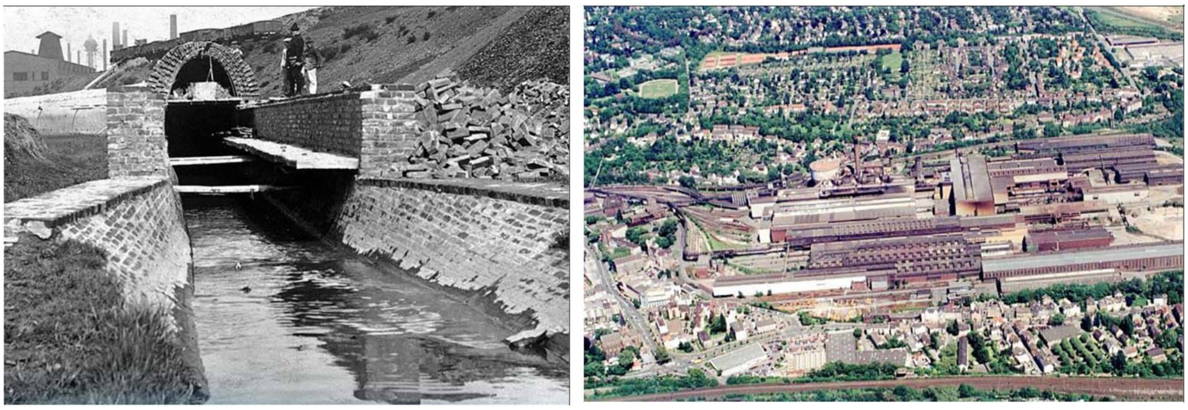

FIGURE 5
Former underground Hoesch Kanal for buried Emscher **(left)** and buried Hörder stream underneath Hermannshütte steelplant **(right).**

FIGURE 6
Map of Lake Phoenix with restored Emscher and Hörder stream (blue) as well as former underground Emscher (dotted line) and the new underground sewer (black).

WFD and a mesotrophic state for the lake (Ministerium für Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen [MULNV], 2021). The streams nearby provide habitats for site-specific sensitive species such as the endemic bullhead (Gerner et al., 2022). Since its creation in 2010, Lake Phoenix has become a hot spot for migratory and local birds (Kretzschmar et al., 2021). An investigation by specialists in 2014 recorded 709 animal and plant species within 24 h, in the lake, the streams, and the surrounding area (Gerner et al., 2022). The restoration project serves as a showcase for urban development even far beyond the region. The Emschergenossenschaft organizes guided tours to explain how the project developed. During the process, the potential success was already perceived by the stakeholders, which produced a positive momentum that helped overcome concerns about costs or about the complexity of this huge project.

India: Daylighting the Godavari River

Historical background

In the past decades, urban planning in India has been mostly driven by economic arguments and the strong competition between cities at the national and international levels (Banerjee-Guha, 2009; Dahake, 2018). This resulted in fast encroachment and severe socio-environmental problems despite that rivers are

FIGURE 7
Daylighted and restored Emscher stream flowing near Lake Phoenix. Photograph: Rupert Oberhäuser, Emschergenossenschaft.

FIGURE 8
Hörder Bach restoration process including **(a)** preparation for the daylighting in front of Hörder castle, **(b)** daylighting Hörder stream via removal of part of the street. **(c)** Hörder stream a few years after daylighting. **(d)** Historical excavations and the lower section of Hörder stream in front of Hörder castle. Photograph: **(a)** Frank Schultze, **(b)** Jochen Durchleuchter, **(c)** Gabi Lyko, **(d)** Nadine Gerner, all Emschergenossenschaft.

considered holy in India (see e.g., recent review on the Yamuna River in Vazhayil and Wantzen, 2022a). Stream restoration is yet mostly limited to the removal of flow obstacles such as invasive plants and plastic litter (Vazhayil and Wantzen, 2022b) or project planning (Sharma et al., 2021) but the concept of daylighting is yet practically unknown. The two case studies

FIGURE 9
Map of Nashik highlighting Godavari River and location of Godavari Ghats (Insert: The Godavari Basin) source: Dahake (2018) Map done by Dahake S.

from the Godavari River presented here show the problems that local movements may face when campaigning against biocultural deterioration (first example, city of Trimbakeshwar) and how they may finally succeed in deculverting a river section (second example from Nashik city). Originating from Trimbakeshwar in Maharashtra, India, the Godavari River flows through Nashik (~30 km downstream from Trimbakeshwar) before emptying into the Bay of Bengal (Dahake, 2018, **Figure 9**). Both cases belong to the four holy cities along the Godavari River, to which pilgrims come to take a holy dip during the Kumbh Mela Hindu festival occurring every 12 years (Singh and Bisht, 2014).

The city of Trimbakeshwar has a residential population of 10,000, but receives up to five million pilgrims during the Kumbh Mela, one of the largest spiritual meetings worldwide (Dahake, 2018). To avoid sanitary problems and accidents, the uppermost stretch became culverted and covered with concrete slabs on a length of 300 m, so that the river completely disappeared from the urban fabric within two periods, 1955–1956 and 1991–1992.

The city of Nashik is flown through the Godavari River on a sector of about 13 km length, of which about a 1.25 km constitutes its religious-cultural center, which is locally known as Goda Ghat. *Ghats* are descending steps situated near the riverbanks for various religious and recreational purposes. During the 17th and 18th centuries, this stretch was divided into 17 river pools (locally named *kund*), around which temples and ghats were built in various periods. These pools evolved to be important for the residents, both, as a water source and spiritually. One of them, the Ramakund, is considered holy by devotees who believe it to be the site where Lord Rama (an important Hindu deity) used to take baths (Nitnaware, 2020).

Before 2003, Nashik municipality followed a similar strategy as in in Trimbakeshwar to promote religious tourism

(Dahake, 2018). The banks of the Godavari River and the stone-paved ghats were refurbished by concrete steps, and the river was bifurcated creating an artificial concrete island on a stretch of 1.5 km. Most of the 17 river pools became culverted or their banks concretized to facilitate access by the pilgrims (**Figure 10**). As a result of this hydrological intervention, the remaining Ramakund pool and the Godavari River fell dry in April 2016, for the first time in 130 years, while seasonal flooding during the monsoon season increased. During the festival, the water level of the Ramakund pool was artificially maintained by deviating water from a nearby river (i.e., it did not contain the holy waters of the Godavari River any more) (Dandekar, 2016; **Figure 11**).

Social-ecological motivations for daylighting

The transformations in water resources management over two centuries in Nashik changed the public perception of the river from a religious-ecological resource to a controlled, political, and economic resource (Dahake, 2018). The accommodation of so many people while maintaining safety and hygienic conditions is a great challenge and has created a paradoxical situation: The attractivity of the Godavari River to support religious tourism has resulted in its culverting, making it invisible. The disappearance of river sections and the deterioration of the remaining holy pools motivated the general public, devotees, and environmentalists to raise their voice against the gradual burial of the riverbed. Thus, in both cases, the drivers for daylighting were a combination of religious motives with evident, negative environmental effects of culverting.

Challenges and problem-solving

In the case of the city of Trimbakeshwar, a project of 15 million USD to improve the environmental quality was completed in 2005; however, the river remained polluted, and the box culverts had not been removed (National Green Tribunal, 2013; Dahake, 2018). In the following time, environmental activists submitted an application to the National Green Tribunal against the degradation of the Godavari, however, the Municipal Council argued that the town was not equipped to handle such large amounts of people during the religious festivals without culverting to warrant the security of the pilgrims and turned down the case (National Green Tribunal, 2013). Thus the headwaters of the Godavari River remain culverted until today.

In Nashik city (**Figure 10**), efforts for daylighting were more successful. In 2015, Devang Jani, a priest and the founder of an NGO for protecting Godavari River (*Godapremi Seva Samiti*), filed a public interest litigation with the Bombay High Court, seeking to de-concretize and restore the river to its original state, which directed the Nashik Municipal Corporation to take the necessary steps within two months. As a result, the Municipality was obliged to de-culvert the 1.5 km river stretch, which improved the depth and width of the river (**Figure 10**). The Nashik Municipal Smart City Development Corporation Limited planned to revive five pools initially and remove the concrete in December 2019. It has restored two pools in June 2020 and is projecting to de-culvert and revive all 17 pools by 2023, under the "Smart cities project" by the Government of India to develop sustainable cities across the country (Ministry of Urban Development [MoUD], 2015; Moudgil, 2019). A first visible result is the reactivation of natural springs after 19 years (**Figure 10**, Nitnaware, 2020).

Lessons learned

While the river's headwaters at Trimbakeshwar is still culverted, the case of Nashik shows that stream daylighting in India is possible, which could have a positive impact on other projects in the future. In India, any citizen can file a case in the judicial court, a so-called Public Interest Litigation (P.I.L.) to advance human rights and equality or to raise issues of broad public concern. This juridical instrument has proven to be efficient in the case of the city of Nashik. Additionally, the new "Smart cities project" by the Government of India, and the cultural identity of the river stretch have facilitated this daylighting project (Dandekar, 2016; Nitnaware, 2020). As with other projects in India (Vazhayil and Wantzen, 2022b), religion, environmental education and/or highly engaged personalities can be strong drivers for stream restoration.

China: Historical canals in Beijing and synchronous stream burial and daylighting in Wuhan

Historical background

Ancient Chinese cities were designed to be integrated with waterways. In history, urban flood prevention with city moats, canals, rivers, drainage ditches, pipes, outlets, and sluices has been adopted in China for thousands of years, starting from the 13th century BC during the Shang Dynasty (Wu, 1989). In 514 BC, the first typical "water city" in China, Great Helu City (now Suzhou City), was built with the plan of eight land gates and eight sluice gates and a network of canals (Ibid.). Since the 1950s, due to urban expansion, rapid population growth, and industrial development, many streams and canals in Chinese cities have been buried or transformed into underground drainage pipes. The number of streams with a basin area of more than 100 km^2 had shrunk from more than 50,000 in the 1950s to 22,909 registered in the "Bulletin of First National Census for Water" by the Ministry of Water Resources in China (Wu, 2019). From the late 1990s to the early 21st century, research on river ecological restoration has emerged in China (Ibid.), including different projects to daylight buried streams.

Daylighting has not been formally promoted in river ecological restoration, and its benefits are not yet widely recognized in China (Chen, 2020). In 2015, the Ministry of

FIGURE 10
(Left) Ramakund covered in concrete slab. **(Middle)** Culverted bed of Godavari at Nashik. **(Right)** Restoration of the river and removal of Ghat islands in the river. Source: Dandekar (2016), Nitnaware (2020).

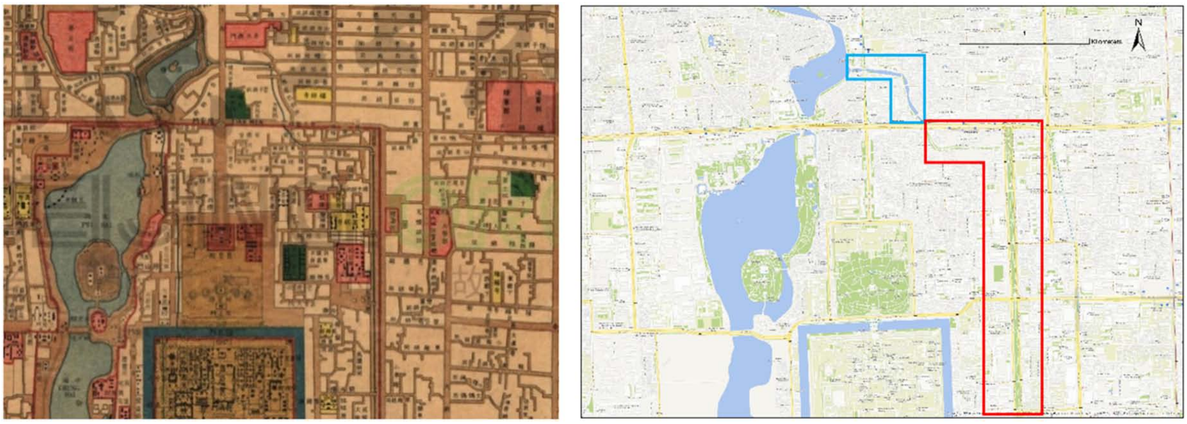

FIGURE 11
Maps of the Yuhe canal in Beijing (created by author, source of the map of Beijing in 1914: Harvard-Yenching Li Collections).

Housing and Urban-Rural Development launched the national call to "eliminate urban black odorous water bodies." Two categories of impaired rivers, the "broken rivers" (in Chinese: 断头浜/断头河", referring to a river that is partially buried), and "dark rivers/streams" (in Chinese: 暗河/暗渠, referring to entirely buried rivers), are both considered the 'source' of water pollution due to their poor self-purification capacity and the lack of a 'live' water source. Consequently, many local water authorities identified the amount and condition of 'broken rivers' at the city scale, and some of them started to carry out daylighting projects to 'make the river flow,' eventually serving the aim to improve the water quality (Xu et al., 2015). The measure is often adopted along with the need to enhance urban flood control capability, integrating into the ' Sponge City' construction (Li, 2019). However, current daylighting practices only take place on the restored river section instead of being systematically organized (Chen, 2020). On the other hand, many local water authorities still convert dirty open channels to box or pipe culverts and bury the streams, considering it as a way to 'eliminate the black and odorous waters' (see examples in Yueyang, Cangzhou, and Laohekou in **Table 5**).

In the early 21st century, a few stream daylighting projects were conducted during archeological excavations of historical canals as cultural heritage sites in China, such as restoring the northern and eastern sections of the Yuhe canal in Beijing (Ye, 2007; Zhang, 2015; **Figures 11**, **12**). The Yuhe River was built as a canal for transportation in the capital city in the Yuan Dynasty (1279–1368) and was used as a municipal drainage channel in the Qing Dynasty (1644–1912). During the Republic of China (1912–1949), the river gradually dried up and degraded. In 1956, it was buried with drainage pipelines (Ye, 2007).

Social-ecological motivations for daylighting

The stream daylighting project – "Historical and Cultural Restoration of the Beijing Yuhe River" – was launched by Beijing's Dongcheng District Government in 2006 and completed in 2017 (Zhang, 2015). The river is part of the historical Grand Canal (Zhang et al., 2022), and the daylighted section is seen as a historical re-appearance representing Beijing's canal culture, with original buildings along the canal banks preserved. However, it does not provide high ecological value, as it is only one meter deep and enclosed by concrete dikes (**Figure 12**).

The daylighting projects presented here were mostly driven be the need to improve wastewater treatment, flood control, and

FIGURE 12
The heritage site of the daylighted section of the Yuhe River (Fan and Da, 2018).

the desire to restore architectural heritage (ancient canals, see **Table 5**).

Challenges and problem-solving

In China, stream burial is still common practice while first stream daylighting projects are already executed. Fast urban growth has resulted in a simplification of open water bodies and culverting of many streams in the past. Currently, sanitation and urban flood risk problems have to be tackled simultaneously in cities with large and dense populations. A typical example for this challenge is the city of Wuhan in the middle of China, with a population of 11.8 million (**Table 5**). Despite being known as "the city of a hundred lakes," decades of rapid urbanization have reduced the lake area significantly from 1789.0 km^2 in the 1920s to 695.3 km^2 in 2015 (Wang et al., 2020). In the same period, many streams have been buried. Stream burial and lake reduction were both driven by the need for construction space, and both produced similar problems such as increased flood risk due to reduced water retention space or too low discharge in the pipes. During the rainy season in June and July, nearly 50% of the annual precipitation occurs in Wuhan (Wu et al., 2020). The urban drainage systems in Wuhan were initially based on the Soviet model in the 1950s, with a low rate of conduit coverage and pipes of a small diameter that were frequently blocked during rainstorms (Lin et al., 2019). Therefore, urban flooding frequently happens during rainstorms (China Meteorological Administration, 2013). To solve this problem, pumping stations and reservoirs have been built, and remaining streams displaying flash flooding discharge were transformed into underground box culverts, e.g., the Jichang and Huangxiao Rivers (**Figures 13A,B**) in the 1980s and the Jiatao River (**Figure 13C**) in 2016 (Wuhan Zhongxin Municipal Construction Co., Ltd, 2016). However, stream burial also occurred due to inadequate water quality in the river, such as in the northern section of the Xunsi River until the confluence of the Xunsi and Yangtze Rivers (**Figure 13D**; Water Resources Bureau of Wuhan, 2019). All these rivers are now only remembered by the name of their covered roads.

On the other hand, the Big East Lake water network project started to build new, open drainage channels unrelated to previously existing rivers and/or streams in 2008 to restore the hydrological connectivity between six lakes and the Yangtze River, e.g., the construction of Chu River in the city center also serves for commercial development (Guo, 2018). Both projects are currently ongoing. A few stream daylighting plans are proposed in the same context, such as the daylighting of the northern section of the Xunsi River (see **Table 5**). From 2010 to 2018, water pollution increased in the culverted section (Water Resources Bureau of Wuhan, 2019). Therefore, Wuhan Water Resource Bureau decided in 2019 to daylight the buried area, targeting to curb water pollution by making the water flow and creating an ecological corridor linking to the Yangtze River (**Figure 13D**; Water Resources Bureau of Wuhan, 2019).

Lessons learned

Stream daylighting is increasingly implemented to improve urban landscapes where water is considered an essential element. Five culverts were daylighted in 2020 in Jiangsu province (Gu et al., 2020), and 34 were daylighted during 2016–2020 in Shenzhen city, Guangdong province (Guangdong Provincial Government, 2021). The new Sponge City Program (General Office of the State Council, 2015) in

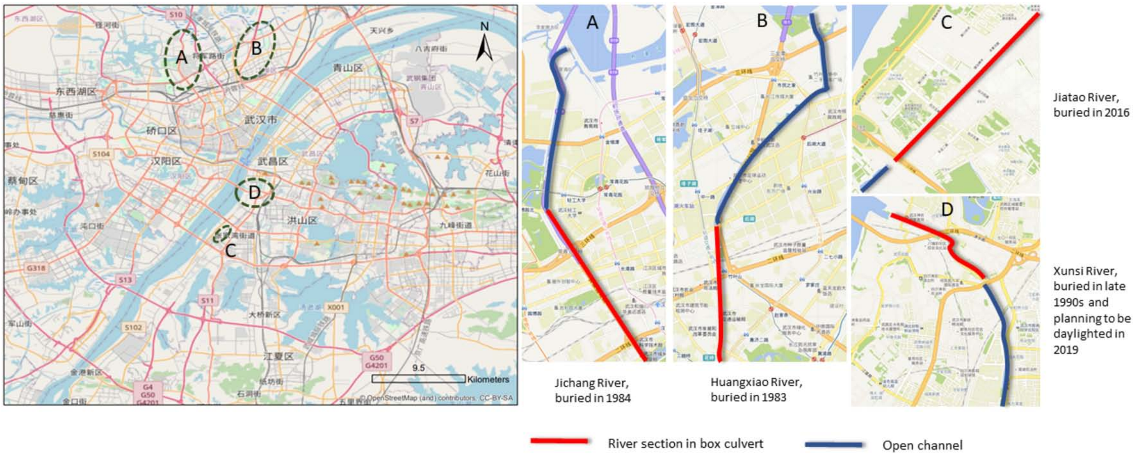

FIGURE 13
Left: map showing four examples for river burial and plans for daylighting in Wuhan. Right: detailed maps for **(A)** the Jichang River, **(B)** Huangxiao River, **(C)** Jiatao River, and **(D)** Xunsi River. Map created by Yixin Cao, based on data from Open street map; Water Resources Bureau of Wuhan (2019).

China widened the purposes of stream daylighting and initiated sizable daylighting projects in certain cities. The Park City Initiative in Chengdu city (Zhang, 2020) also tends to daylight a series of streams to restore the urban river connectivity. However, the case of Wuhan also confirmed the empirical evidence found in Wuxi: In a Chinese context, the notion of "stream daylighting" is not conceptualized or structured yet. "Daylighting streams" are seen as a single technique approach rather than being a common goal or sense of river management (Chen, 2020).

Taiwan: The first three streams daylighted

Historical background

Since the earliest urbanization, flooding and river pollution are two main challenges for urban hydrosystem management in Taiwan. Lying across the Tropic of Cancer, the climate of Taiwan island is influenced by the East Asian Monsoon and receives abundant precipitation in summer, with typhoons most likely striking between July and October. The mountain ranges in the island center are surrounded by narrow coastal plains. This results in a high flood risk in densely colonized urban areas, where more than 70% population resides. The early construction of sewer canals dates back to the Qing Dynasty (1636–1912), and has been regularly modernized (Chou, 2013). Since 2003, a completely new sewage system has been implemented, which resulted in that 65.17% of the wastewater water being treated in 2021, but it still does not keep pace with rapid urbanization for its high construction cost (Sewage System Office Construction and Planning Agency Ministry of the Interior, 2021). The percentage of moderate-polluted river sections has decreased from 82.1% in 2011 to 63.9% in 2020, whereas the highly polluted river sections have increased from 6.8% in 2011 to 9.5% in 2020 (Environmental Protection Administration, 2020a). Amongst the total 2,933.9 km of the 50 larger rivers in Taiwan island, 81 km (2.8%) of them are highly polluted, and 615.2 km (21%) of them were moderately polluted in 2019 (Environmental Protection Administration, 2020a). Much wastewater is still directly discharged into urban rivers without significant treatment. Like in other urban areas of the Global South (Wantzen et al., 2019), river channelization and concealing are popular methods for dealing with flooding and water pollution in Taiwan (Chou, 2013). Urban rivers and even their headwaters have been channelized since the 1970s (Chou, 2012). However, flood risks have been increasing in urban areas with climate change impacts, such as Typhoon Nari in 2001, resulting in 94 people dead, as well as a total economic loss of 0.75 billion € (TVBS wireless satellite TV station, 2002).

Social-ecological motivations for daylighting

With increasing climate change impact, the concrete channels and culverts can no longer defend against catastrophic flooding events, as the catastrophic floods often exceed the flood control capacity of concrete channels. Therefore, all three projects described in the following were motivated by the objective to improve flood management, sanitation, and the socio-ecological benefits from urban riverscapes at the same time.

Challenges and problem-solving

The major challenge for stream daylighting in Taiwan is the combination of high urban flood risk with an insufficient sewer system. Since 2001, restoration of open river has gradually gained popularity (Chou, 2016), with more than 70 river restoration projects have been recorded (Taiwan River Restoration Network, 2021), but so far, only three cases of stream daylighting have been registered (**Table 6**), namely, Laojie Stream in Taoyuan City (Chou, 2016), Lu Stream and Liu Stream in Taizhung City (Wang, 2015), Yunlin Stream in Yinlin County (Yunlin County Government, 2017). The local governments played a key role in initiating and implementing the projects. All projects presented here implemented similar approaches: First daylighting the stream; then improving the water quality by intercepting domestic waste water to water treatment plants; lastly, improving the river landscape and providing social benefits such aesthetic and recreational values (**Table 3**).

The Laojie Stream daylighting in Taoyuan City is the first successful stream daylighting example with cross-sectoral elaboration in Taiwan (Huang, 2018). Taoyuan City, in the northwest of the Taiwan island, is home to a population of 2.1 million. Rivers in the city are generally short and narrow. With a length of 36.7 km and a catchment area of 81.95 km^2, the Laojie Stream is the longest stream flowing through Taoyuan (**Figure 14**). In 1986, to avoid the unpleasant smell from the stream and increase the space for car parking and street vendors, a 725 m long stream section was buried (Taoyuan government, 2011). Since then, the stream has been even more heavily polluted. In 2009, two industrial companies, Huaying Ltd. and Youda Ltd. obtained permission from the local authority to directly discharge wastewater into the buried section (Environmental Protection Administration, 2020b). In 2011, to improve water quality, riverine landscape, and flood management, the Taoyuan government planned 1.1 billion NT$ (32.7 million €) to daylight the covered section (Environmental Protection Administration, 2020b).

The daylighting project provides ecological and social values by de-culverting the stream (Chou, 2016). In 2011, after holding over 50 open meetings with stakeholders to gain their support, the 725 m culverted section was finally daylighted (**Figure 14**). The river channel was widened to 35–36 m and deepened to 5–6 m to meet the 100-year return period flood prevention requirement. The zone along the daylighted stream was greatly improved, e.g., cycle tracks and parks were constructed. The river banks in the park were restored with gravel and boulder substrate, and vegetation was re-introduced on the gentle bank slope (**Figure 15**). Newly installed sewage interceptors divert domestic sewage to wastewater treatment plants to improve water quality (Environmental Protection Administration, 2017). The first river-themed educational center, Laojie Stream Education Center, was built to exhibit the outcomes of the daylighting project. It displays the river's development history and daylighting processes through models and interactive devices. A variety of educational activities, such as film projection and guided tours to the riverside, are carried out regularly.

Lessons learned

The benefits of stream daylighting are not yet widely recognized in Taiwan, and stream burial is ongoing, which is similar to the two previous examples. The Laojie Stream daylighting is considered successful in terms of its ecological (**Figure 14**) and social benefits (Environmental Protection Administration, 2017); however, many challenges remain. The cost for building water treatment plants and interceptors are enormous. In the case of the Yinlin Stream project, they made up 85% of the total funding (Yunlin County Government, 2017). Thus, overall sewage treatment and water quality are still low, which is limiting the biological benefits of daylighting projects. Communication between public and government regarding flood risk reduction needs to be improved to support future river protection (Chou, 2016).

Historical analyses to rediscover buried streams

The examples cited above show that in old urban agglomerations, traces of streams buried centuries ago may be difficult to reveal, as reliable hydrographical maps are rarely available. Moreover, specifically in fast-developing cities, the intergenerational memory and the cultural relatedness to urban water bodies have often been interrupted (Wantzen et al., 2019; Khirfan et al., 2021). This makes it difficult to identify candidate streams for daylighting. The re-discovery of ancient courses of streams often requires extensive analyses of different types of source material, such as historical maps, paintings or photographic records (see Broadhead et al., 2015 for a review). Sometimes, road names still remind the existence of a stream and may even reveal its uses prior to culverting. In our case studies, e.g., in Zurich, the word "Bach" (German for "stream") appears in names, such as "Hegibachplatz," or "Mühlebachstrasse," or in Wuhan, the ending "he" (which means "river" in Chinese) in street names such as "Huangxiaohe, Xunsihe, Jiataohe" (see **Figure 12**). The central avenue in the capital of Mato Grosso (Brazil), Cuiabá, is named "Prainha," which means "small beach" to remember the place where people used to wash their clothes, where today, cars are running on a six-lane road (Wantzen et al., 2019). Restoration engineers are rarely trained for these activities. Collaboration with historians is highly recommendable, as the rediscovery of the historical heritage of urban streams may become a strong element of motivation for daylighting (Broadhead et al., 2013; Khirfan et al., 2021; Usher et al., 2021). In the following, we describe the historical development of urban streams in a mid-sized western European city and their rediscovery.

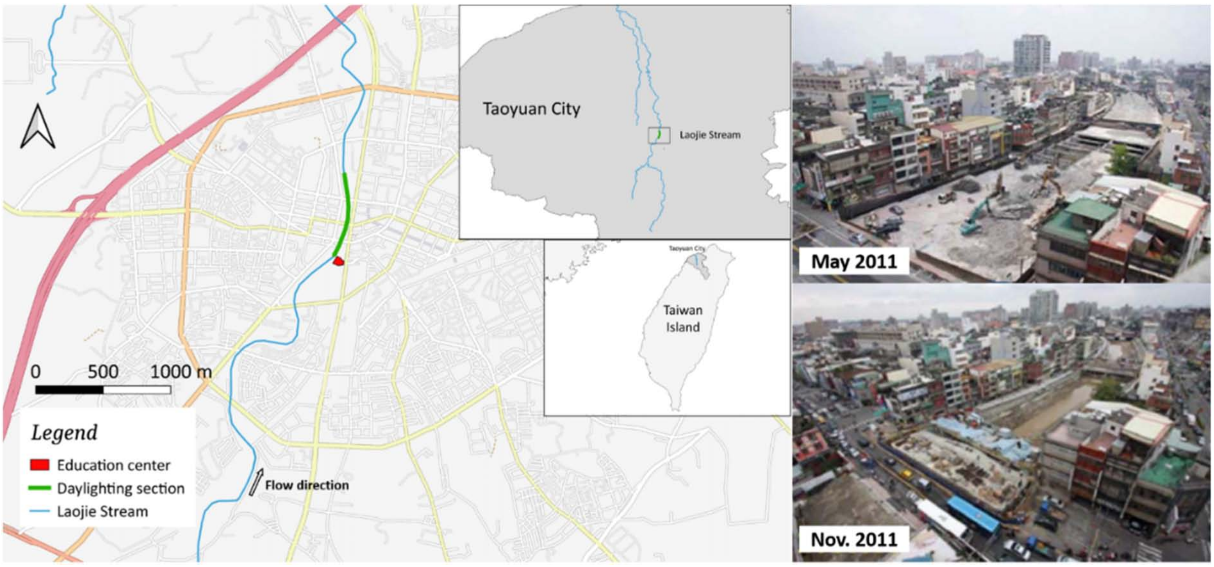

FIGURE 14
(Left) Map showing the daylighting section of the Laojie Stream. Map by Chaozhong Tan. **(Right)** Photographs showing the Laojie Stream before (above) and after the daylighting (below). Photographs from https://www.wra.gov.tw/News_Content.aspx?n=25153&s=88373. ©Taoyuan Department of Water.

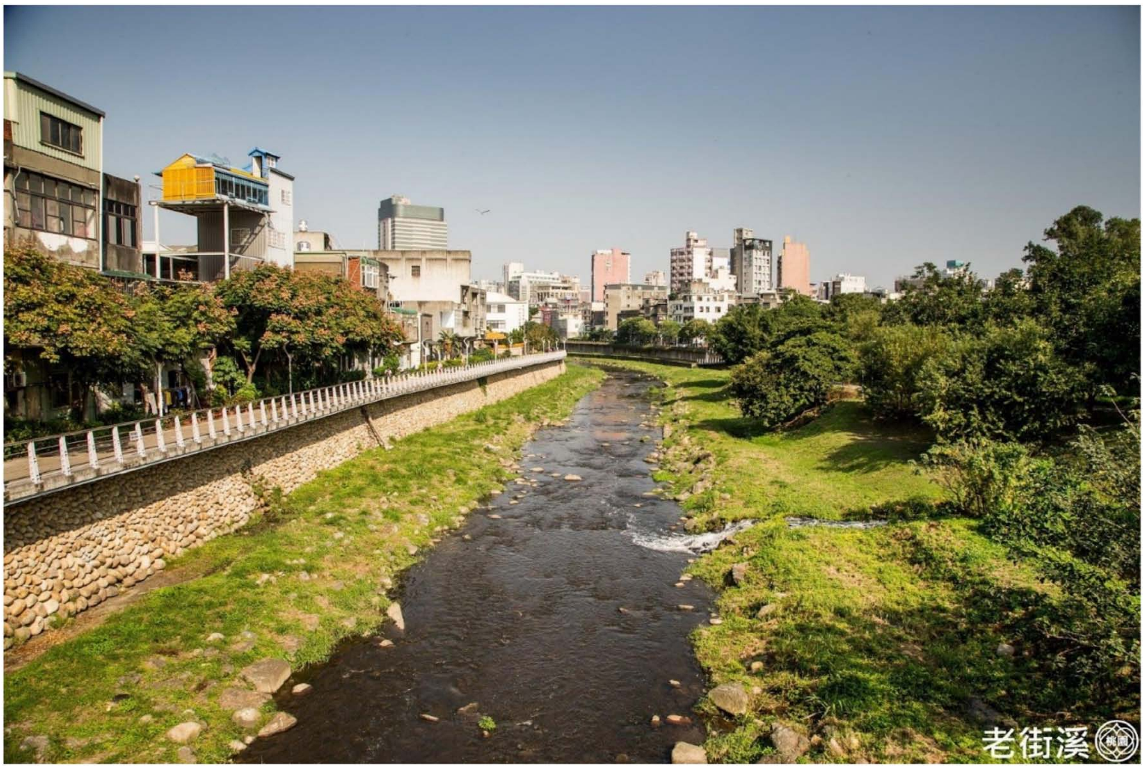

FIGURE 15
The Laojie Stream and its riparian zone. ©Taoyuan City Government 2019.

Case study: Rediscovery of disappeared streams in Tours, France

Combining old maps and historical literature, we could identify the position and the historical development of three urban streams in the city of Tours (135,000 inhabitants) that were filled or buried in the mid-19th century. The city center is an ancient interfluvial floodplain limited by the borders of the Loire River to the North and the Cher River to the South (Maillard, 2003). Since the Middle Ages, several streams crossing the city and draining into either one of these rivers (Plan Local d'Urbanisme, 2019) were used as a superficial sewer system. Under Louis XI (∼1461–1483), one of them, the Saint-Anne stream, had been enlarged to a 35–40 m wide canal that connected the Loire and the Cher River for a long time (**Figure 16**). It served as a shortcut for navigation to avoid the difficult passage through the several shallow confluences of the two rivers downstream Tours. During the fixation of the quays of Tours from 1774 to 1777, the opening of the canal towards the Loire was closed to reduce flood risk. After dike construction along the Loire in 1813, passage for wastewater drainage was reopened, but the canal became pestilential, and finally, it was completely filled up in 1846 (Audin, 2013). Today, its former bed is forming the alignment of an avenue.

Two other streams previously existing in the city [Ruisseau de Dolve (Dolve brook) and the Ruisseau de l'Archevêque (Archbishop stream)] are flowing underground today, buried into pipes, but their position and course could be reproduced from old maps and paintings (**Figures 16**, **17**). Both streams originally ran in parallel, crossing the city from east to west, then coalesced before flowing into the Saint-Anne canal (Audin, 2013).

The Dolve brook was already used as a dumping site in 1597. Due to its low current velocities, it gradually became silted up and flooded its banks regularly. In 1840, action was taken to pave the riverbed with stones to avoid floods, but this failed. At the same time, the municipality allowed residents to cover the stream flowing next to their homes at their own expense. In 1880, the council decided to cover the 1,300 m of the Dolve Brook. The stream was canalized by a pipe 1.5 m large and 1.8 m high. Deposits of thick sand and silt layers (up to 1 m) make regular dredging necessary. Part of the historical trace of Dolve brook is now remembered by the street name, Rue de la Dolve (Audin, 2013).

The Archbishop stream originally served to supply the inhabitants with drinking water. In 1872, it was partially filled up, and the resulting wetland was transformed into a public park "Parque des Prébendes d'Oé" with a small lagoon still existing today. After 1880, the stream was partially covered by a brick vault, and in 1940, it was still visible in some streets (Audin, 2013). The remaining open sections served later as an open sewer, which had to be regularly cleaned and maintained, and produced a terrible smell, complained by inhabitants (Basset, 2011). This resulted in a stepwise overlay of the stream with concrete, which ended in the 1960s. Only elder citizens remember this today. After the drying up of the Saint Anne canal, both streams were diverted southwards to the Cher River. The concrete culvert outlet constructed in 1990 is the only visible remains of these streams today. Thus, the search for culvert openings or the analysis of digital elevation models may deliver the first hints of where to begin historical analyses in search of lost streams. Recently, the track of the ancient streams has been re-identified and been integrated into a concept of "living history tourism," i.e., interested people can follow the tracks of the streams by bicycle and become informed about past events, culture and architecture by a guide. This fight against oblivion may become the seed for a restoration project in the future.

Decision making for selecting candidate streams for daylighting projects

Being one of the most cost-intensive approaches in river restoration, the selection of the most promising candidate streams for daylighting (in terms of potential benefits to be achieved) requires specific attention. Each case of potential restoration projects is characterized by a social and biophysical environment, making it necessary to deliver solutions tailored to this situation. A detailed analysis of the local setting implies the practical steps to solve the specific problems (see **Figures 1**, **2**). However, to make projects more efficient, it is necessary to establish Best Management Practices (BMPs) and standard procedures in a daylighting restoration referential. In the past, due to a lack of reporting on projects in databanks, badly defined targets, and specifically due to lacking scenario planning and monitoring of the expected (and undesired) effects of restoration, huge amounts of money have been invested without assessing the effects of diverse projects, e.g., for urban river restoration in Europe (Feld et al., 2011; Zingraff-Hamed et al., 2017). The few case studies presented here and the detailed review by Khirfan et al. (2020a) both evidence that stream daylighting is a new field of ecological restoration in the Global South and it is gaining a global momentum. As with urban hydrosystem restoration in general (Wantzen et al., 2019), this situation bears the chance to develop global databanks (such as that by Khirfan et al., 2020b), which can be used for (i) systematic improvement of BMPs, (ii) the choice of the most promising candidate streams for daylighting, and (iii) communicating the best examples globally. In the following, we make an attempt to synthesize elements that may help to select the most promising streams in a city for daylighting projects.

FIGURE 16
(A) Cassini's map of Tours (1770) showing the Saint-Anne canal in the West of the city (Géoportail, 2020). **(B)** Engraving showing the confluence of the Saint-Anne canal with the Loire (Tours archives).

Criteria used to prioritize restoration

Different authors have delivered sets of – partly coinciding – arguments and criteria to initialize daylighting projects (see Khirfan et al., 2020a for a review). In the Zurich case, available space, legal, technical, and economic aspects (Conradin and Buchli, 2004), and social connectivity (Broadhead et al., 2013; Kondolf and Pinto, 2017) were crucial elements of choice. Klesius (1999) listed seven parameters to prioritize restoration, being available space, soil and water contamination, financial resources, safety issues, and public opinion or attitudes toward the environment. Moses (2003) suggested physical, cultural, political, and economic factors, in combination with the preferences of landowners and institutional bodies which govern the objectives and types of the restoration. A good candidate stream for daylighting can be determined by assessing projected costs, site conditions, and even political struggles and public resistance, as found by Buchholz and Younos (2007), who deliver a detailed survey of case studies in the USA. Koshaley (2009) defined four categories of criteria, including technical factors, urban economics and politics, institutional, and ecological aspects.

Combining results from the literature with expert knowledge from our case studies in 3 European and 3 Asian regions, we established six categories for selecting streams for daylighting: biophysical setting, practical aspects, political aspects, social aspects, and climate change and associated measurable criteria to these categories (see **Table 7** for an overview and **Supplementary Annex II** with details).

Proposal for a decision support system

Based on the selection criteria (**Table 7**), we here suggest a preliminary DSS as a baseline for further refinements (**Figure 18** and **Supplementary Annex II**). This DSS is based upon the thematic issues that arose from the 6 case studies presented here, combined with those of further case studies in the literature cited in this review. At its current state, it has to be considered as a list of criteria (and their positive and negative expressions) that we recommend for consideration in decision-making. We present the parameters that should be taken into consideration but we currently do not weigh the importance of the individual parameters. Locally, some criteria may be more important than others, so this DSS needs to be adapted to the local situation.

Candidate streams can be prioritized according to their ratio of positive and negative criteria (**Figure 18**) that are suggested to conduct a comprehensive measurement of daylighting stream's performance and benefits. Each indicator's properties (i.e., metric, source, assessment factor) are also specified (**Supplementary Annex II**) to weigh the potential benefits and risks of a daylighting project. The overarching goals of this procedure should be to prioritize the available stream candidates with the highest positive potential ecological and social impact of the project and the best financial/political support, and to maximize the stream-daylighting objective by modeling related risks and opportunities. The feasibility and availability of the technical options for restoration also play an important role in decision-making, however, due to the highly variable local conditions, we could not integrate technique-specific recommendations into this DSS. Instead, we provide some general suggestions resulting from the case studies presented here (see next section).

Favorable conditions, limitations and practical aspects for stream daylighting projects

Summarizing the practical experience from our case studies, the best success chances for daylighting projects in general

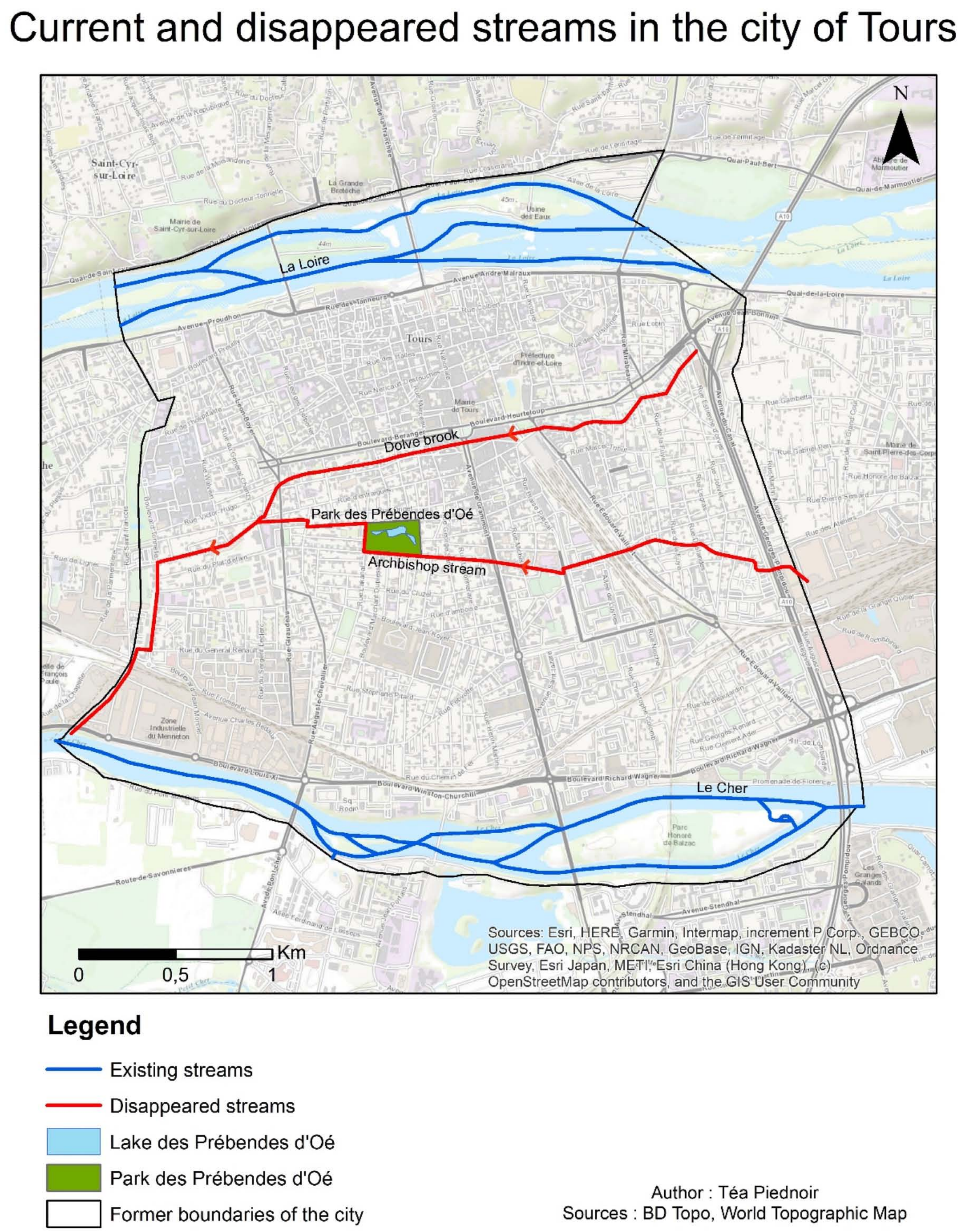

FIGURE 17
Map showing the current and buried streams in center Tours.

were found in areas where (i) the separation of residual water (rainwater, surface runoff) from sewage provided a significant economic benefit, (ii) reconstruction of streams was cheaper than that of pipelines, while maintenance or repair of sewage pipelines/channels was expensive, (iii) climate change-driven risks urged the redesign of the urban hydrology, (iv) housing

TABLE 7 List of the criteria for prioritization of daylighting projects.

Category	Criterion	Description
Technology	Stream burial characteristics	Basic characteristics of the buried stream, such as the length of the covered section, connections of the stream to the sewer system
Environment and ecology	Water quality parameters	Physico-chemical variables, such as pH, water temperature, total nitrogen
	Species diversity	Number and abundance of aquatic species (bioindicators, invaders)
	Sediment conditions	Sediment type, impervious area, and possibly occurring contaminants
	Land use conditions	Land use type and catchment area of the covered river, share of private and public properties, total covered area
Economy	Implementation costs	Purchase of terrain, engineering, compensation measures (e.g., rebuilding costs)
	Maintenance costs	Future maintenance (cleaning, cutting)
Institution	Legislation	Existing laws/policies favoring daylighting (including "Sponge City" approaches)
	Public support	Public financial funding, or institutional/administrative support
Society	Citizen involvement	Social movements, NGOs, neighborhood associations in support of daylighting
	Improved quality of life	Potential effects of improved socio-environmental quality (health, wellbeing), esthetic, culture and heritage effects
Climate change	Disaster risk reduction	Reduction of flood risk and urban heat stress

areas were decommissioned and newly built, (v) projects were supported by neighborhood-associations or specific sponsors, (vi) coordinated projects with many interested stakeholders could be realized, or (vii) projects at the city center could boost local business activities.

There were also some criteria, such as high costs, high risks, or the lack of available public space that made citizens opposing the project (Chou, 2016). The cases of the Sonnette stream in France, the Emscher in Germany, and the Laojie Stream in Taiwan show how timely stakeholder involvement and series of debates may help to find solutions.

In the following, we summarize expert knowledge from our case studies and diverse daylighting projects worldwide in the context of the problems and potential benefits (**Figures 1, 2**) according to the criteria we developed above (**Table 7** and **Figure 18**). These may help to further develop the DSS by weighing individual parameters, or to develop scenarios for individual daylighting projects.

Environmental and technological aspects

Planform and topography

Practical suggestions from the Zurich project (DVWK, 2000; Hugentobler and Gysi, 2002; Conradin and Buchli, 2004; Kari, 2004) and other case studies (see above) generally include that (i) streams with perennial flow should be favored for restoration (as empty stream beds occurring during a drought or low-flow periods could be abused for littering), (ii) longer stream sections should be clearly favored over short sections to re-establish a migration corridors for animals (in both directions) and the downstream transport of sediments. However, in some cases of severely modified urban landscapes, even "aquatic islands" without visible ecological improvement may represent a "window to nature," or a "window to historical heritage" (as with the Sonete and Hoerder streams, above) especially when these are integrated into recreational activities, as it is the case with the city of Freiburg, Germany (Medearis and Daseking, 2012) or with the Cheonggyecheon stream in Seoul, Korea, which has a high value for environmental education and aesthetics (Lee and Anderson, 2013).

Cross-section and floodplain

Many people understand a "stream" just as the streambed with a maximum filling to bankfull level (Fuchs et al., 2017). However, all river systems interact with their species-rich floodplain, where most biogeochemical processes occur, and hydrological extremes become buffered (Tockner et al., 2000; Junk and Wantzen, 2004). Therefore it is necessary to have available space around the stream and a relatively small impervious surface in the watershed (Moses, 2003). Sufficiently broad riparian zones also represent important areas for groundwater recharge (Vidon and Hill, 2004). The floodplain slows the movement of the water by floodplain vegetation (Madsen et al., 2001), therefore increasing the hydraulic retention time for sediment deposit and flood reduction (Bond et al., 2020). Both these arguments increasingly gain importance in the context of climate change (see below). These restored urban floodplain zones can be designed as "Human-River-Encounter Sites," whereby care has to be taken to avoid conflicts between interests for human wellbeing and environmental functions, respectively, biodiversity (see Zingraff-Hamed et al., 2021 for review and discussion). The contrasting solutions from the Emscher case study show how streambed architecture can be tailored according the available riparian space, which is the decisive parameter concerning the 'degree of naturalness' that can be achieved by a daylighting project (see **Figures 7, 8**).

Sediment quantity and quality

Sediment transport may become problematic in urban streams. Therefore, the Zurich project used to have bedload collectors to have sediment deposited and removed them before they enter the city in order to prevent clogging. Novel legislation such as the European WFD (Terrado et al., 2016) does not allow this sediment removal anymore, therefore, some of the previously planned daylighting projects could not be implemented any more. Juridical solutions for these special cases are needed. Other projects could not be realized as the terrain contained contaminated soils that would have required an expensive restoration (Chou, 2016).

Water quality

Low domestic wastewater treatment ratio hampered the social and biological benefits of daylighting projects in Taiwan (see above). Improper water has a strong negative effect on human perception of nature and may cause opposition to urban stream restoration in general (Wantzen et al., 2019). Treatment of wastewater and removal of contaminated sediments should therefore anticipate or parallel any stream restoration activity, and in the case of daylighting, may support the acceptance of a proposed project. Moreover, the higher the water quality, the higher the probability to have sensitive species (including rare or protected fauna and flora) recolonize the restored stream section (Feld et al., 2011), make the site more attractive for the urbanites and improve the value of the project as an example for further daylighting (see Emscher, Zurich, and India cases in this paper and see the discussion about social and ecological targets in the case of the Cheonggyecheon stream in Seoul, South Korea, e.g., Lee and Anderson, 2013; Khirfan et al., 2020a).

Economic aspects

Real estate

Due to the intensive land use and limited open spaces in dense urban areas, river restoration in cities is generally much more costly than that in rural areas. Thus, daylighting projects can be easier implemented if open space is available, e.g., in public parks or areas, or if private properties are offered to restore the streams. Stream daylighting projects can be well integrated into urban renewal or re-design plans of brownfields or abandoned industrial areas (see the example of the Phoenix Lake, above), and even be practiced by real estate companies as a leverage to increase the real estate value by the presence of blue/green elements. However, as with all urban redesign projects, care should be taken to avoid gentrification (Khirfan et al., 2020a) despite that it is easier to convince the actors to restore the stream if daylighting is likely to increase the property values (Pinkham, 2000).

Sanitation

Restoring culverted streams that were used as sewers is costly, especially in areas without sufficient wastewater treatment (Broadhead et al., 2013, 2015). Therefore, daylighting projects that try to substantially improve the water quality require the construction of additional wastewater treatment plants and associated infrastructures, which can be very expensive. Due to this reason, restoration costs in Taiwan (**Table 6**) were orders of magnitude higher than in France (**Table 3**).

On the other hand, a comparison between the costs generated by the maintenance or renewal of the pipes and the cost of the daylighting project can help to motivate the restoration project. In the Zurich case, several daylighting projects were supported by the economic argument (see above) during the refurbishment of the sewerage system, and the separation of wastewater from surface water reduced treatment costs (see also Broadhead et al., 2013). Moreover, old sewer canals are often buried deep in the ground, which causes high maintenance costs (Kari, pers. obs., and see Emscher example). A combined upraising of the sewer canal and separation of canal and surface water conduct (i.e., the daylighted stream) can lower the maintenance costs compared with the continuation of the "business as usual" scenarios so that the restoration may become economically beneficial.

Societal and political aspects

Governance

Societal drivers are crucial for any restoration project. These can occur in top–down (regulation by government), bottom–up (social movements) or alternative (e.g., real estate price) directions (Wantzen et al., 2019). Daylighting projects may specifically benefit from social movements, as the issue of "rebirthing" of a stream (or nature in general) can mobilize political engagement in a bottom-up movement (see, e.g., Vazhayil and Wantzen, 2022b and our examples from France and India), especially if NGOs already exist, such as the "Quartiervereine" in Switzerland. These act then as corridors of power between the citizens and the politicians (Stadt Zürich, 2020). New settlements or redesign of urban quarters can also leverage political engagement (see the Emscher case study, above). The examples from India and China (above) have shown that religious motives and the wish to re-establish built historical canals can also become strong drivers for stream restoration, including daylighting.

Laws

Legal prescriptions for restoration such as the WFD in Europe or adaptive strategies to Climate Change set a framework and can help to generally support daylighting projects (see examples from France). In Switzerland, the improved, legally binding protection of open streams is certainly a major breakthrough for the conservation of nature, but it may also lower the willingness of landowners to allow daylighting. As any open stream automatically has protected banks, the re-appearance of a stream on a private ground may become equivalent to an interdiction of further constructions in the riparian zone, which is equivalent to a considerable financial loss for the owner (Kari, personal observation). On the other hand, many housing areas are demolished and completely rebuilt to adapt to current needs and regulations, which allows re-opening streams (see Emscher example). In Switzerland, daylighting is prescribed by law if the canal structures were modified during

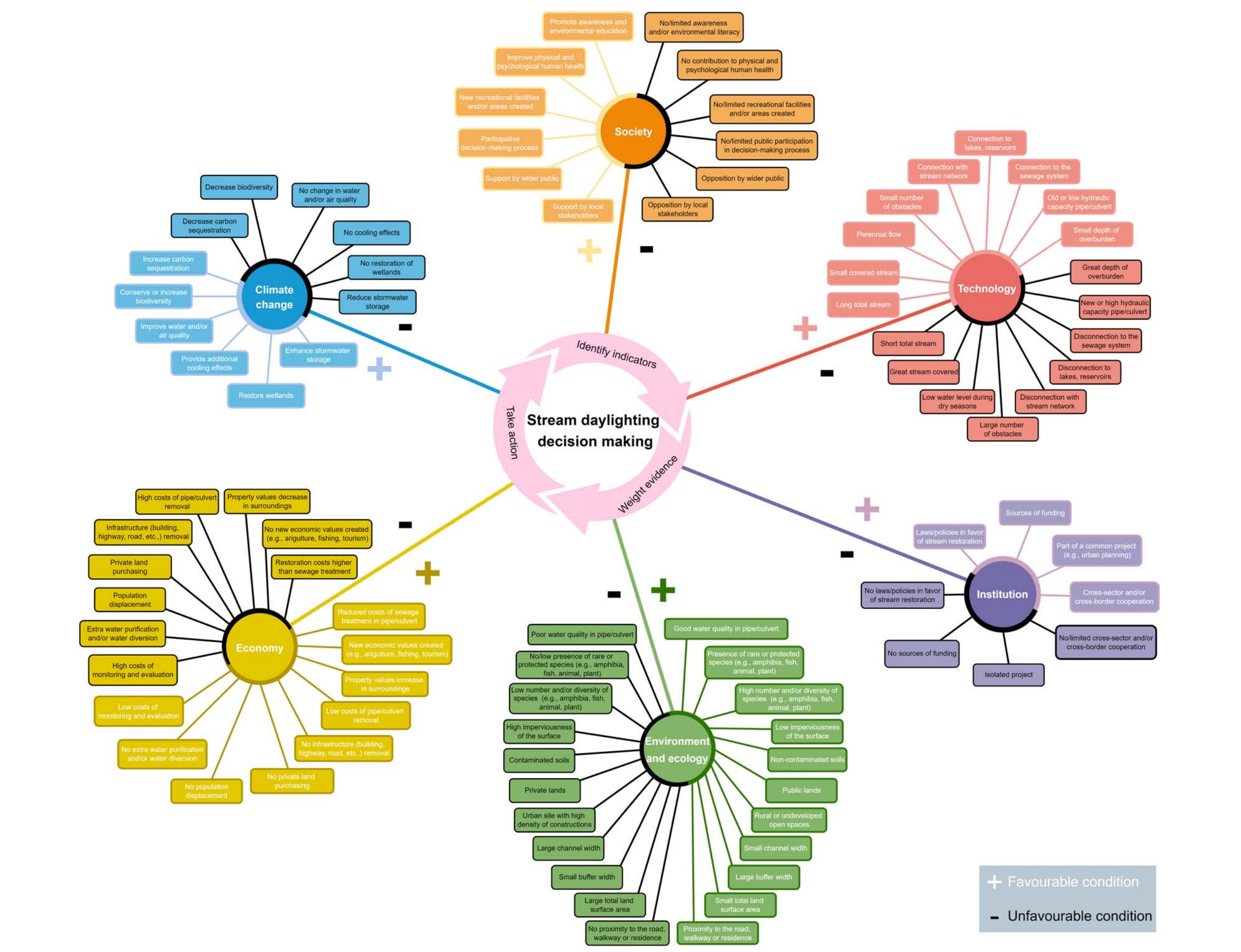

FIGURE 18
Elements for a preliminary decision support framework for the choice of stream daylighting candidates.

the reconstruction (Entsorgung + Recycling Zürich, 2003). However, the negotiation process to apply the law can be very time-consuming. The Taiwanese government has passed a law that declares the construction on covered rivers illegal (Taoyuan government, 2011). The implementation of this law required over 50 workshops to get support from the public, which delayed the project implementation (Chou, 2016).

Climate change

Flood effects

Due to climate change, extreme situations of droughts and floods occur more frequently (Magnan et al., 2021). Moreover, cities produce excess surface runoff due to sealing and soil imperviousness during storm events (Wang et al., 2021). The recent extreme flood events in Central Europe and China in July 2021 underline the need to prevent flood-prone cities in a much larger dimension than before (Netzel et al., 2021). Stream daylighting may contribute to the solution of this problem. Opening the stream and providing a wider riparian flood zone allows conveying much larger quantities of water and sediments across the city, thereby reducing damages in buildings and physical injuries (see case study of Wuhan, above). In some cases in Taiwan, the local population was afraid that green-blue spaces would not be able to defend the floods as gray infrastructures do (Chou, 2016), therefore, the hydrological modeling substantiating the safety of the project needs to be clearly communicated.

In this context, the exchange between surface water and groundwater is a critical issue. Despite that the ecological ideal is to establish this kind of connectivity for the sake of biogeochemical processes, recharging of the aquifer and support of biodiversity, daylighted streams (or stream sections) may locally need to run in sealed beds, in order to avoid erosion and risk for buildings (Zurich case) or to avoid contamination of the aquifer (Taiwan case). Vertically permeable stream beds and riparian zone clearly contribute to the "Sponge City" approach (see China case).

Even if there were damages caused by floods in the restored stream area, these have a much higher resilience (resulting in lower repair costs), as streams are naturally dynamic systems that are adapted to changing environmental conditions. Moreover, a visible stream is an important element of improving the personal risk perception of the citizens, which is elementary for long-term mitigation measures and sustainable urban flood management (Fuchs et al., 2017; Netzel et al., 2021).

Drought effects

Climate change also causes that many open streams fall dry during rainless periods. Dry-fallen stream beds are perceived just as a trench, and passers-by often misuse them for litter disposal, with an accumulating tendency (once the first plastic bag was seen, others follow, Kari, personal observation). When these streams become rewetted again, the combination of plastic litter with natural sediments may quickly block the drainage (Honingh et al., 2020), especially when reopened stream sections enter the canalization again. Urban water managers may allocate water into these streams to maintain the water flow (see Zurich example), but this dotation is limited by the available water reservoirs.

Urban heat waves

The permanent heating of urban agglomerations worldwide requires better cooling corridors that reduce heat in extremely hot spots and carry away heat. Restored urban streams, combined with a network of blue-green corridors, reduce air temperatures by evapotranspiration (Ampatzidis and Kershaw, 2020). Urban streams and wetlands connect surface and ground water and may absorb excess water during rainstorms, provided that sufficient space and adequate porosity of the soils are given.

Conclusion

Daylighting provides significant ecological, social and economic benefits; however, this kind of stream restoration is much more costly and may encounter greater socio-economical constraints in cities than in open areas. We hope that our interdisciplinary approach helps to advance the understanding of stream daylighting from different perspectives, to improve the selection process of candidate streams, and the performance of daylighting projects. The precursor of a DSS generalized from the knowledge and experience of professionals presented here may be used to identify and prioritize streams for daylighting. However, each stream has its individual characteristics, and the criteria presented here need to be tested using datasets from different regions. Further research will be needed to select the best management practices. It would go beyond the scope of this paper to deliver detailed information on the engineering aspects and how to attribute distinctive measures to specific local scenarios. Further studies in this field are needed, specifically concerning the above-mentioned "degree of naturalness" that can be achieved by restoration of strongly artificialized ecosystems, and the corresponding re-establishment of biological and cultural diversity.

The comparative Global North-South comparison presented here has corroborated some of the structural, biophysical, and socio-economical differences in patterns and processes that are known for the restoration of open urban streams (Wantzen et al., 2019), especially the limited administrative, juridical and financial support for projects in most of the Global South. We fully acknowledge the limitations of our dataset, however, we think that some generalizations about the differences and similarities about drivers and hindrances in the European and Asian examples can be made.

The higher population size (including the floating populations of pilgrims in India) combined with lower degree of wastewater treatment and the higher impacts by climate change seem to make daylighting projects more complicated and at the same time more urgent in Asia, when compared with the Europe. The case studies in China and Taiwan have shown that daylighting and stream burial still co-occur, and both are driven by flood risk. Compared with the Global North, daylighting projects in the Global South were less well documented (mostly in local media reports) and yet less well-integrated into urban (re-) design concepts. We could find one first example from India, but have been unable to find any document on daylighting in Latin America and Africa. Khirfan et al. (2021) have delivered arguments in favor of a possible daylighting project in Amman, Jordania.

As the concept of daylighting and documented results of projects that can help to improve technologies and practices are better developed in Europe (and the Global North in general, see analysis by Khirfan et al., 2020a), this calls for a better, bidirectional exchange of knowledge in the context of the UN Decade of Restoration (Fischer et al., 2021). As a first step, successful projects and need to be better documented and communicated beyond borders. By documenting little known cases from the from the Global South, we hope to contribute to this process.

Obviously, solutions cannot be copied from one place to another. Therefore, our case studies have focused on the motivation and decision-making process in the studied regions. Comparisons between different geopolitical and societal systems can support solution finding in socio-ecological restoration in different ways. First, despite large local differences, there are also generalities in the evolution of human-river-relationships (Wantzen et al., 2016, 2022; Hein et al., 2021) that may help to identify the current socio-environmental status of the studied system and the nearest and future targets for restoration projects. Moreover, seeing one's study object through the perspective of another cultural background may reveal overlooked (or forgotten) thematics and inspire innovative approaches. Lastly, a mutual learning process (the so-called North-South-South dialog) can be incentivized, appreciating the best social and environmental management elements from different sociocultural backgrounds (see Saric et al., 2019; Wantzen et al., 2019, 2022 for discussion).

Considering that there are enormous global challenges due to planetary boundaries (Rockström et al., 2021) and that the growing human population is increasingly living in cities (United Nations, 2019), stream daylighting may deliver solutions to several global problems occurring in cities, such as flood and drought risks, urban heat islands, human health and wellbeing, and the need for improving environmental education and human-nature relationships. Stream daylighting techniques need to be adapted and improved to become an integral part of the hydrological buffering concept in cities. Thus, urban stream restoration (including daylighting) will need to be integrated into a universal urban hydrological budget.

Lastly, urban streams are habitats for non-human and human species, and they generate biocultural linkages, the River Culture (Wantzen et al., 2016) and social connectivity (Kondolf and Pinto, 2017). Daylighting can help to restore these linkages. Culverted streams would be delighted to be daylighted.

Author contributions

KW: concept development and major part of the writing. TP: literature review Europe and study in Tours, France. FK and ML: case study Zurich. YC and CT: case study China. AV: case study India. NG and MS: case study Emscher. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2022.838794/full#supplementary-material

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